



## **The National Ignition Facility (NIF) and High Energy Density Science Research at LLNL**

**Presentation to:**  
**IEEE Pulsed Power and Plasma Science Conference**

**C. J. Keane**  
**Director, NIF User Office**  
**June 21, 2013**

**Lawrence Livermore National Laboratory**

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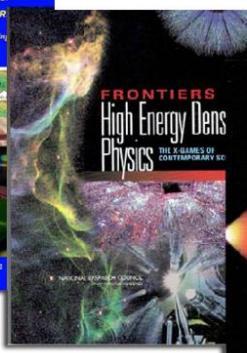
# Advances in laser/pulsed power drivers and related simulation, diagnostic, and other capabilities enable exciting new opportunities for scientific discovery



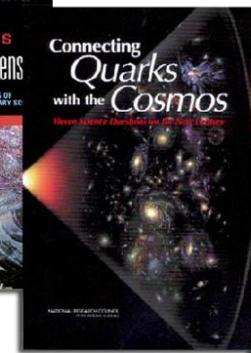
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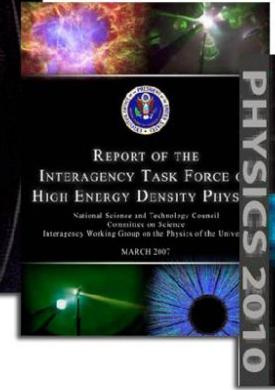
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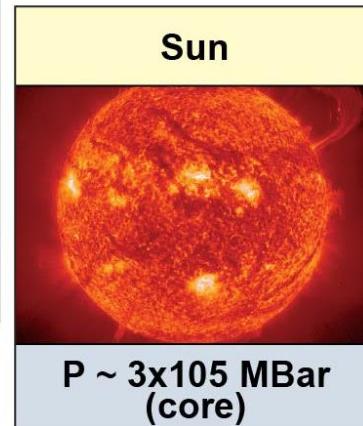
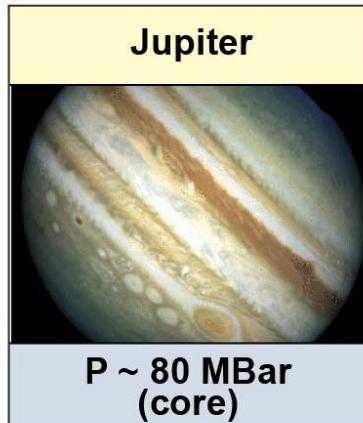
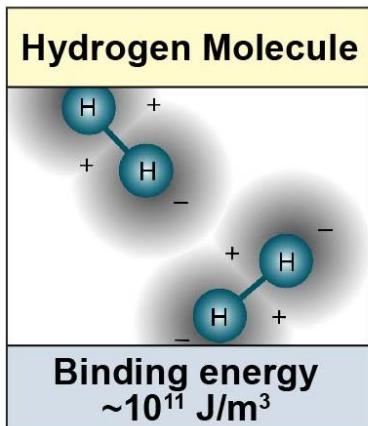
2010



- “Science on (NIF, Omega, Jupiter, Z,...) science is more than HED science”



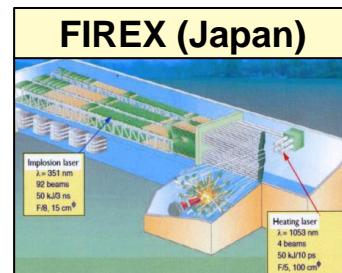
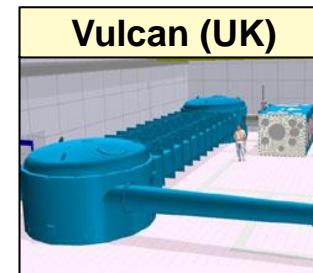
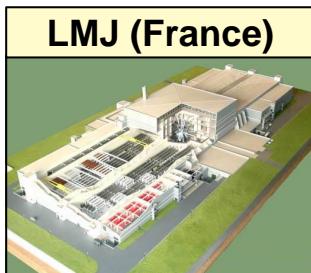
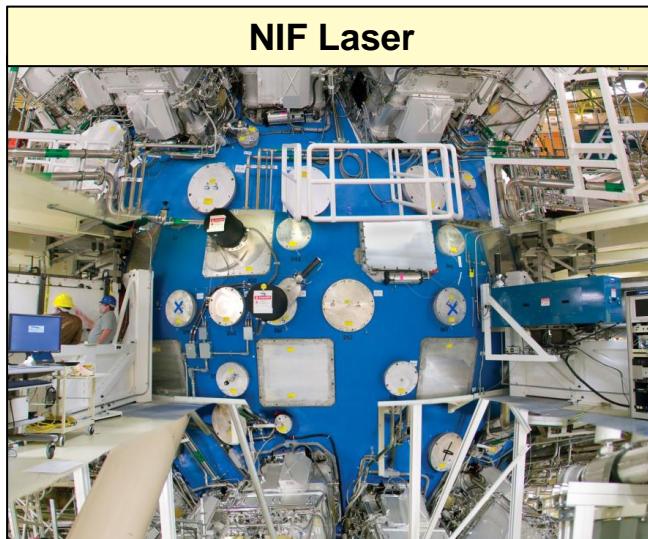
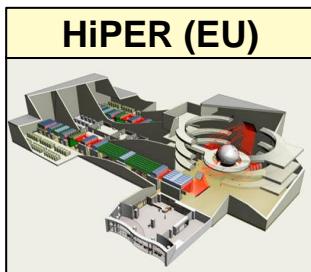
## 2003 NRC Report on High Energy Density Physics defines HED science as $P > 1$ Mbar ( $10^{11}$ J/m<sup>3</sup>)



1 atm = .98 Bar



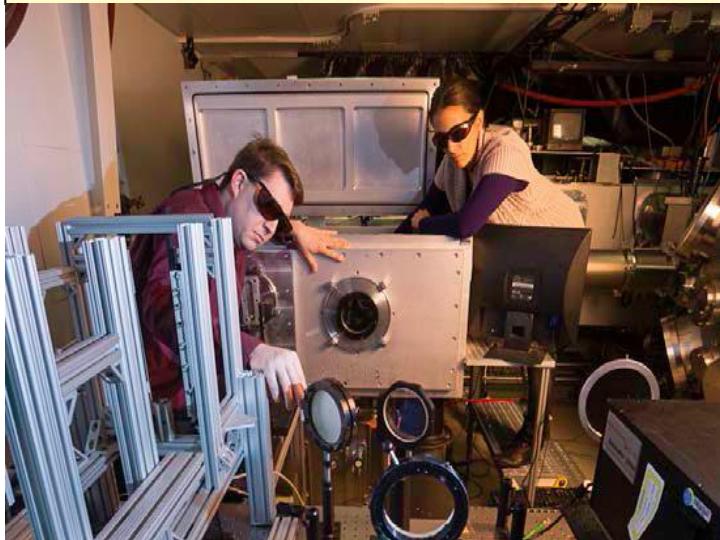
Advances in drivers, diagnostics, targets, and simulation are driving evolution of this field worldwide





## The NIF and Jupiter lasers are the primary HED facilities at LLNL

Jupiter



“Intermediate scale” facility ideal for student training

NIF



Large-scale facility for high energy applications



# Jupiter Laser Facility



Expanding High Energy-Density Science

# Jupiter has operated as a user facility since 2008, with 112 peer-reviewed publications through FY2012



**ARTICLE**

Received 10 Jul 2012 | Accepted 23 Oct 2012 | Published xx xxx 2012 | DOI: 10.1038/ncomms2225

**Nanosecond white-light Laue diffraction measurements of dislocation microstructure in shock-compressed single-crystal copper**

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 117, E09009, doi:10.1029/2012JE004092, 2012

**Shock vaporization of silica and the thermodynamics of planetary impact events**

R. G. Kraus,<sup>1</sup> S. T. Stewart,<sup>2</sup> D. C. Swift,<sup>2</sup> C. A. Bolme,<sup>2</sup> R. F. Smith,<sup>2</sup> S. Hanel,<sup>2</sup> B. D. Hammel,<sup>2</sup> D. K. Spaulding,<sup>2</sup> G. Hicks,<sup>2</sup> J. H. Eggert,<sup>2</sup> and G. W. Collins<sup>2</sup>

Received 15 March 2012; revised 17 August 2012; accepted 18 August 2012; published 21 September 2012.

[1] The most energetic planetary collisions attain shock pressures that result in abundant melting and vaporization. Accurate predictions of the extent of melting and vaporization require knowledge of vast regions of the phase diagrams of the constituents. We report the first shock-compression experiments that have conducted uniaxial shock-and-release experiments, where quartz was shocked to a state sufficient to initiate vaporization upon isentropic decompression (hundreds of GPa). The apparent temperature of the decompressing fluid was measured with a streak-camera imager, and the bulk density was inferred directly onto a streak window. To interpret the observed post-shock temperatures, we developed a model for the apparent temperature of a material isentropically decompressing through its liquid-vapor coexistence region. Using this model, we calculated the density and temperature of shocked quartz and silica and calculated the entropy on the quartz Hugoniot. The silica post-shock temperature measurements, up to entropies beyond the critical point, are in excellent qualitative agreement with the shock-wave-phase-diagram calculations of the Hugoniot. Shock-and-release experiments provide an accurate measurement of the temperature on the phase boundary for entropies below the critical point, with increasing uncertainties near and above the critical point entropy. Our new criteria for shock-induced vaporization of quartz are in excellent agreement with the critical point entropy on the Hugoniot. As the thermodynamics of other silicates are expected to be similar to quartz, vaporization is a significant process during high-velocity planetary collisions.

Citation: Kraus, R. G., et al. (2012), Shock vaporization of silica and the thermodynamics of planetary impact events, *J. Geophys. Res.*, 117, E09009, doi:10.1029/2012JE004092.

**Two-dimensional Jinst**

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(Received 8 March 2011; published 8 February 2012)

**PRL 109, 145006 (2012)** PHYSICAL REVIEW LETTERS week ending 5 OCTOBER 2012

**Dynamics of Relativistic Laser-Plasma Interaction on Solid Targets**

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(Received 6 May 2011; published 5 October 2012)

A novel time-resolved diagnostic is used to record the critical surface motion during picosecond-scale relativistic laser interaction with a solid target. Single-shot measurements of the principal shock show a redshift decreasing with time during the interaction, corresponding to a slowing-down of the hole-boring process into overdense plasma. On-shot full characterization of the laser-pulse energy rebids simulations of the experiment without any free parameters. Two-dimensional particle-in-cell simulations yield rebids that agree with the data, and support a simple explanation of the slowing-down of the critical surface based on momentum conservation between ions and reflected laser light.

DOI: 10.1103/PhysRevLett.109.145006

PACS numbers: 52.38.-r, 52.27.Ny

**on-equilibrium warm dense gold**

Yonea<sup>a</sup>, Byoung-ick Cho<sup>b</sup>, Phil Heimann<sup>b</sup>, Eric Schwengler<sup>a</sup>,

<sup>a</sup> R.A.C.T.

measured the time evolution of the phase shift at the front and back surfaces of gold nano-films excited with a 150 fs ( $\lambda = 400$  nm) laser pulse. The thickness of the filaments ( $\sim 30$  nm) is much smaller than the laser wavelength. The phase shift at the front surface of the film increases as the laser fluence increases. The front and back sides of the film behave similarly, indicating uniform heating by the laser. As the pump fluence is increased, the phase shift on the front side is higher than that measured on the back side. The phase shift is proportional to the laser fluence.

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**RAPID COMMUNICATIONS**

**PRL 108, 065701 (2012)** PHYSICAL REVIEW LETTERS week ending 10 FEBRUARY 2012

**Evidence for a Phase Transition in Silicate Melt at Extreme Pressure and Temperature Conditions**

D. K. Spaulding,<sup>1</sup> R. S. McWilliams,<sup>2</sup> R. Jeanloz,<sup>1,2</sup> J. H. Eggert,<sup>3</sup> P. M. Celliers,<sup>3</sup> D. G. Hicks,<sup>3</sup> G. W. Collins,<sup>3</sup> and R. F. Smith<sup>3</sup>

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(Received 3 August 2012; published 28 December 2012)

Laser-driven shock compression experiments reveal the presence of a phase transition in  $\text{MgSiO}_3$  over the pressure-temperature range 300–400 GPa and 10 000–16 000 K, with a positive Clapeyron slope and a volume change of  $\sim 6.3 (\pm 2.0)$  percent. The observations are most readily interpreted as an abrupt liquid–liquid transition in a silicate composition representative of terrestrial planetary mantles, implying potentially significant consequences for the thermal–chemical evolution of extrasolar planetary interiors. In addition, the present results extend the Hugoniot equation of state of  $\text{MgSiO}_3$ , single crystal and glass to 950 GPa.

DOI: 10.1103/PhysRevLett.108.065701

PACS numbers: 64.70.Ja, 62.50.-p, 64.30.Jk, 91.45.Bg

**original bulk location as linear 1D surface defects in the Pt overlayer (Fig. 3E). A simplified schematic of the self-terminating Pt deposition process in Fig. 3E is shown in Fig. 3F.**

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**PHYSICAL REVIEW B 86, 245204 (2012)**

**Orientation and rate dependence in high strain-rate compression of single-crystal silicon**

R. F. Smith,<sup>1</sup> R. W. Minich,<sup>1</sup> R. E. Rudd,<sup>1</sup> J. H. Eggert,<sup>1</sup> C. A. Bolme,<sup>2</sup> S. L. Bryggum,<sup>3</sup> A. M. Jones,<sup>1,\*</sup> and G. W. Collins<sup>1</sup>

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High strain-rate ( $\dot{\epsilon} \sim 10^6$ – $10^8 \text{ s}^{-1}$ ) compression of single crystal Si reveals strong orientation- and rate-dependent precursor nucleation. At these high compression rates, the peak elastic stress,  $\sigma_{\text{peak}}$ , for Si [110]–[110], and [111]–[111] is close to the Hugoniot elastic limit. In contrast, the  $\sigma_{\text{peak}}$  with Si samples from uniaxial compression to a three-dimensional relaxed state is exponentially dependent on  $\dot{\epsilon}_{\text{peak}}$  and independent of initial crystal orientation. At later times, the high elastic wave speed results in a temporal decoupling of the elastic precursor from the main inelastic wave. A rapid high- $\dot{\epsilon}$  increase in the measured elastic stress at the onset of inelastic deformation is consistent with a transition from dislocation flow mediated by thermal activation to a phonon drag regime.

DOI: 10.1103/PhysRevB.86.245204

PACS numbers: 61.72.uf, 62.20.E-, 62.20.D-

1497



# COMET is used by NIF to calibrate and test diagnostics

## Studies of the mechanisms of powerful terahertz radiation from laser plasmas

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Recently Terahertz (THz) radiation from laser-produced plasma has attracted much interest since plasmas can work at arbitrarily high laser intensity. This paper will discuss the generation mechanisms of plasma-based THz radiation.

### I. INTRODUCTION

Terahertz radiation has been attracted much interest due to increasingly wide applications. Though THz radiation can be generated with various ways, it is still a big challenge to obtain strong tabletop sources. Plasmas, with an advantage of no damage limit, are promising medium to generate strong THz radiation.<sup>[1]</sup> THz radiation from femtosecond laser-induced plasma filaments in low density gases (particularly in air) has been reported. However, the radiation is found to be saturated with pump laser intensity. Recently THz radiation from intense laser-plasma interactions has also been reported. In principle, the higher the laser intensity can be, the more easily high. The typical intensity of a multi-terawatt laser system is higher than  $10^{19}$  W/cm<sup>2</sup> (up to  $10^{21}$  W/cm<sup>2</sup> with a Petawatt laser). Using such ultraintense lasers, strong THz radiation with energies even up to mJ is expected. Intense laser-plasma interactions provide new opportunity to greatly enhance the THz source strength. On the other hand, the THz radiation can also be used as a new way to diagnose the interactions.

We have symmetrically studied strong THz radiation from solid targets driven by relativistic laser pulses. The experiments were carried out using femtosecond and picosecond laser systems, respectively. THz radiation with a pulse energy of tens  $\mu$ J/sr (driven by femtosecond laser), even  $\sim$ mJ/sr (driven by picosecond laser) is observed. In this talk, the THz polarization, temporal waveform and the peak frequency dependence on the laser energy will be presented. We find that the radiation is dependent on the preplasma density scale length. We believe that the THz radiation is probably attributed to the self-organized transient fast electron currents formed along the target surface for steep plasma density profile, while the linear mode conversion mechanism when a large scale preplasma is presented.

### II. THZ RADIATION FROM FEMTOSECOND LASER–SOLID INTERACTIONS FOR STEEP PLASMA PROFILE

Hanster *et al.* first demonstrated the generation of THz pulses with energies of 1  $\mu$ J/sr from solid aluminum targets irradiated by laser pulses at an intensity  $\sim 10^{19}$  W/cm<sup>2</sup>.<sup>[2]</sup> They believed that the THz radiation originated from the electric fields emitted from the longitudinal ponderomotive force at the critical density surface. THz pulses with 0.5  $\mu$ J/sr were also observed by Saganaka *et al.* from Ti solid foil targets at a little bit lower laser intensity  $10^{17}$  W/cm<sup>2</sup>.<sup>[3]</sup> They proposed an “antenna” model to explain the observation, in which assumes that the electrons spread over the whole target and the target acts like an antenna. The spectrum of THz radiation from laser driven plasmas generated on a copper wire was measured using free-space electro-optic sampling by Gao *et al.*<sup>[4]</sup> However, no clear evidence was found to show that the target size affects the THz radiation spectrum.

Our femtosecond experiments were carried out using the Xtreme Light (XL-IR) Ti: sapphire laser system at the Institute of Physics of the Chinese Academy of Sciences. A linearly-polarized laser pulse with an energy up to 150 mJ in 100 fs at 800 nm focused on a 20  $\mu$ m thick copper foil at an incidence angle 67.5° using an f/3.5 off axis parabolic mirror. A calibrated piezoelectric detector aligned in the laser specular direction was used to measure the THz pulse energy. Figure 1(a) shows the dependence of the THz pulse energy on pump laser energy. Each data point is taken by an average of  $\sim$ 10 shots. The energy of the THz radiation monotonically increases with laser energy. For the laser energy of 130 mJ, the THz energy is up to 5.5  $\mu$ J in 0.11 sr. The temporal waveform was measured by a modified, single-shot electro-optic method with a chipped laser pulse, where a 1-mm thick ZnTe was used as the sampling crystal. It is found that the THz peak frequency is about 0.5 THz. The frequency can be tuned by changing the laser incidence angle and plasma conditions.

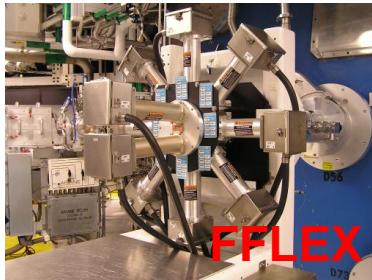
The strong THz radiation was measured and found that the net current could have been excited in the plasma. In the interaction of a relativistic laser pulse with a solid foil due to the confinement of the spontaneous quasistatic magnetic and electrostatic fields at target surface, a lateral



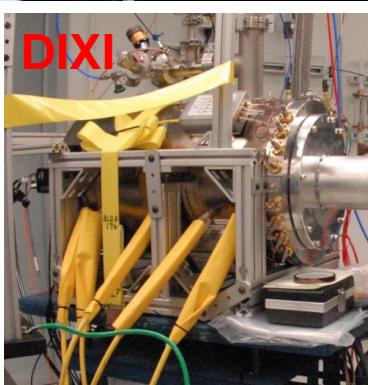
nTOF



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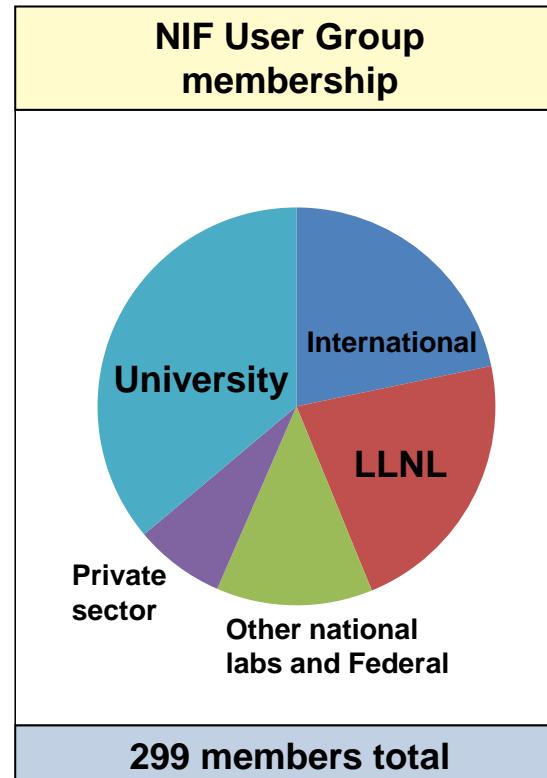
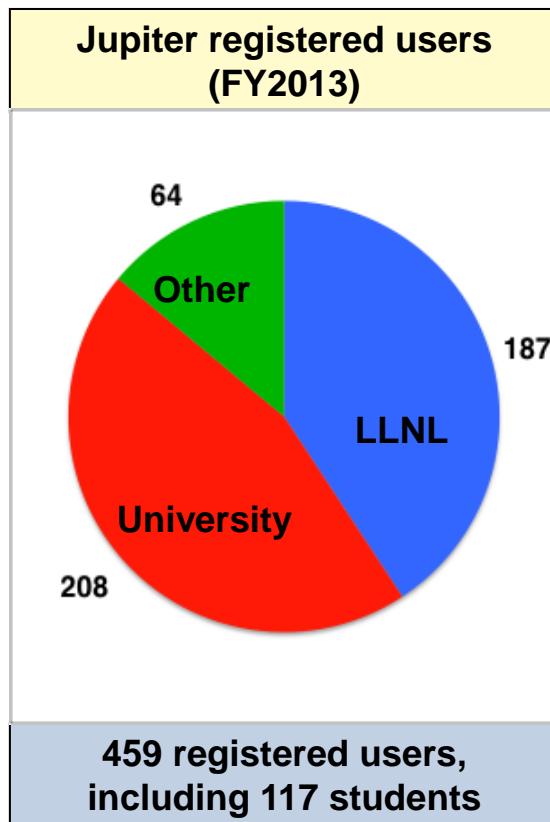


## **NIF/Jupiter User Group meeting: Feb. 10-13, 2013; approx. 200 attendees, 16 countries**

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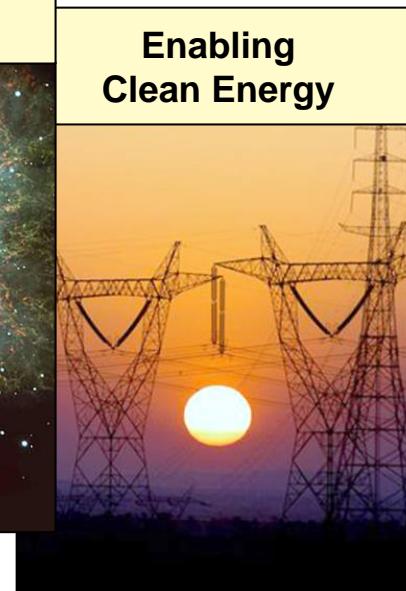
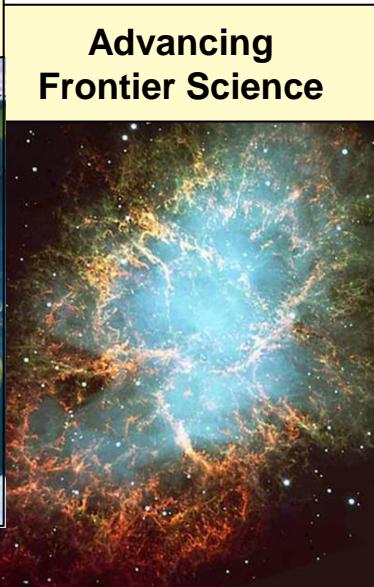
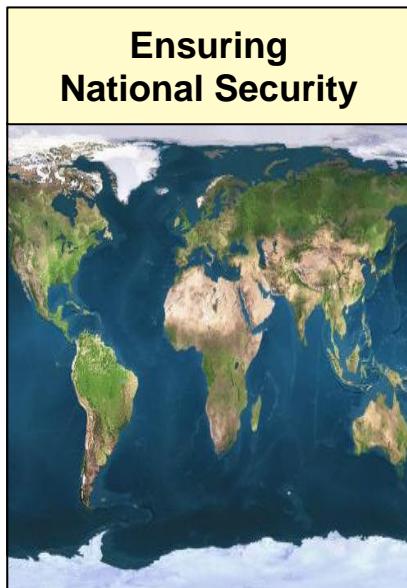
## Overview of NIF and JLF user communities

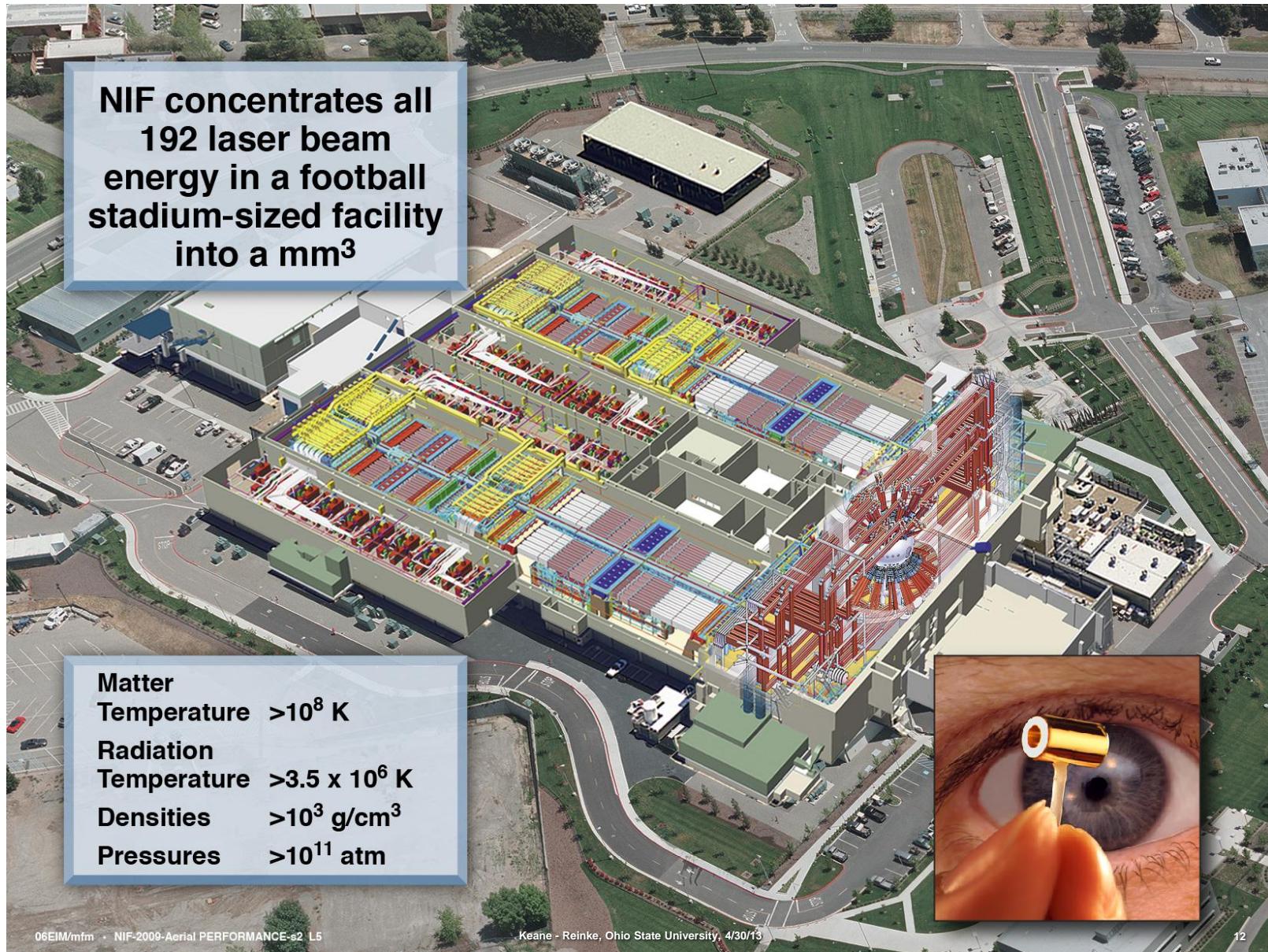


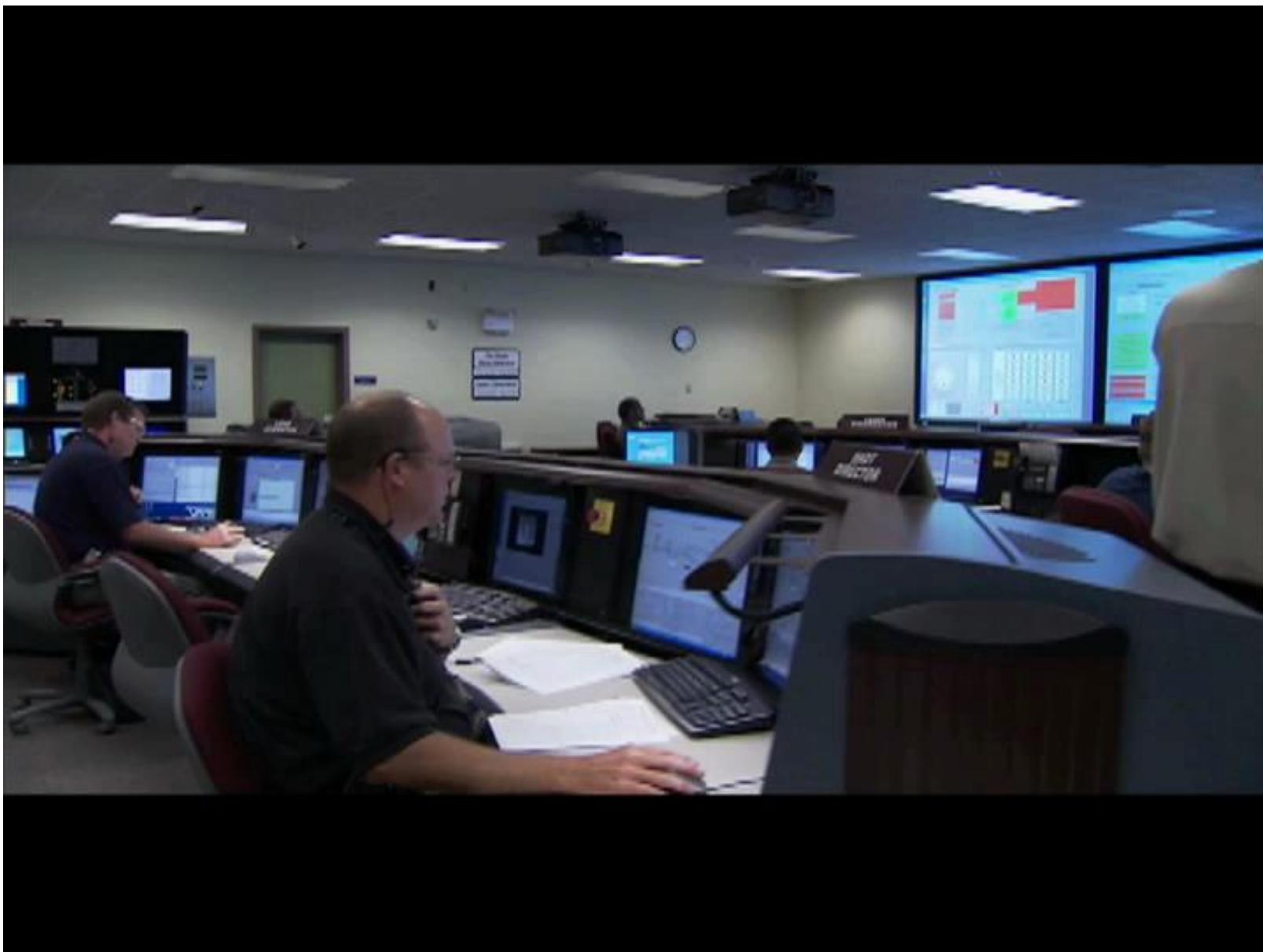


## NIF missions

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## From relativistic phenomena to ~ 1 eV condensed matter physics- NIF allows a wide range of experiments

Laser	Diagnostics	Targets	Simulation
<p><b>Wide variety of pulse shapes, w/ few percent reproducibility and precision (1.855 MJ/533 TW exceeds specs)</b></p>	<p><b>Photon and particle diagnostics w/ high spatial, temporal, spectral resolution</b></p>	<p><b>Spherical, planar, machined perturbations, exotic materials,..</b></p>	<p><b>Experimental design via target and laser simulation tools</b></p>

**NIF will also bring an unprecedented new capability- the ability to study burning plasma physics**



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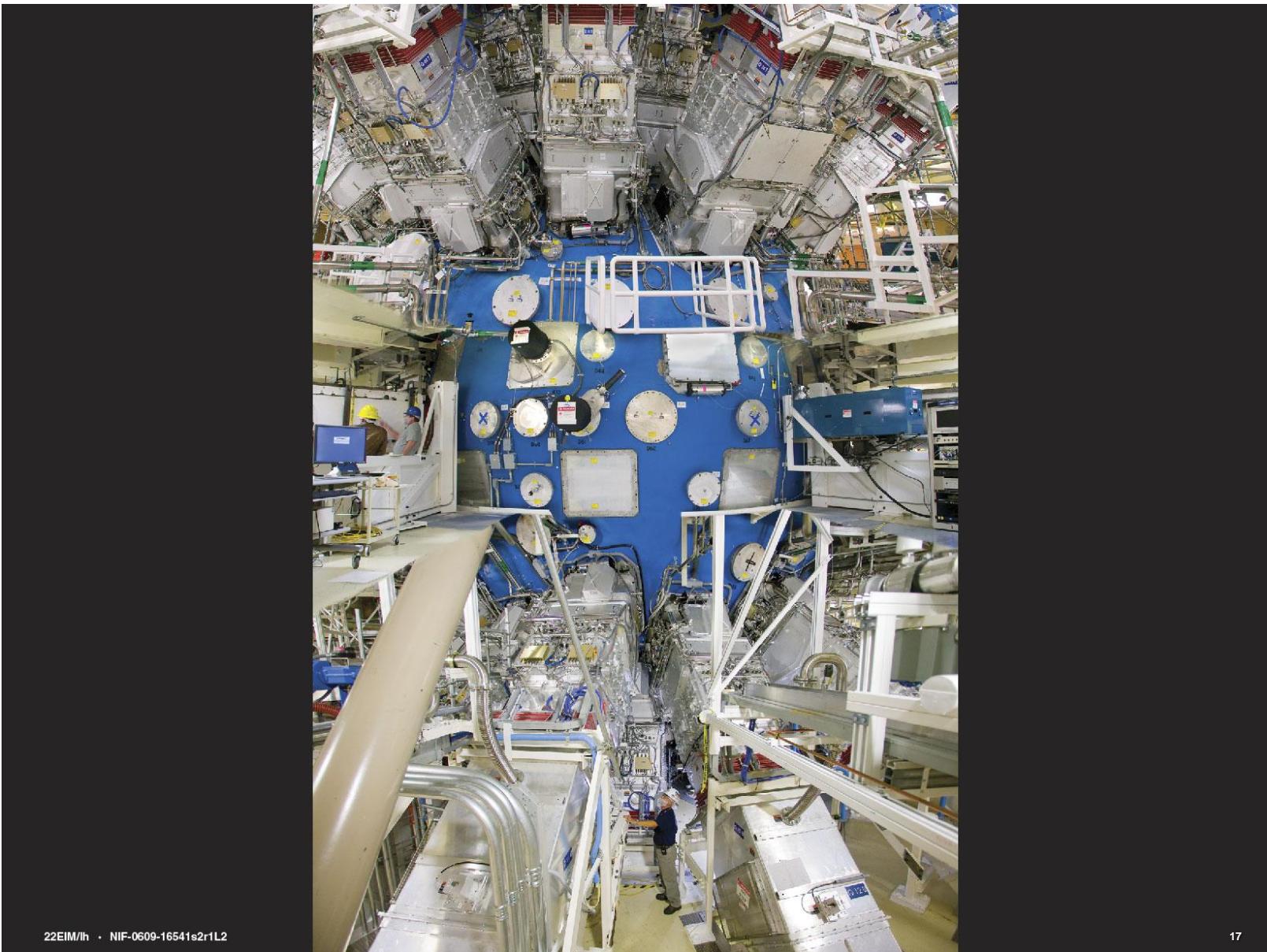
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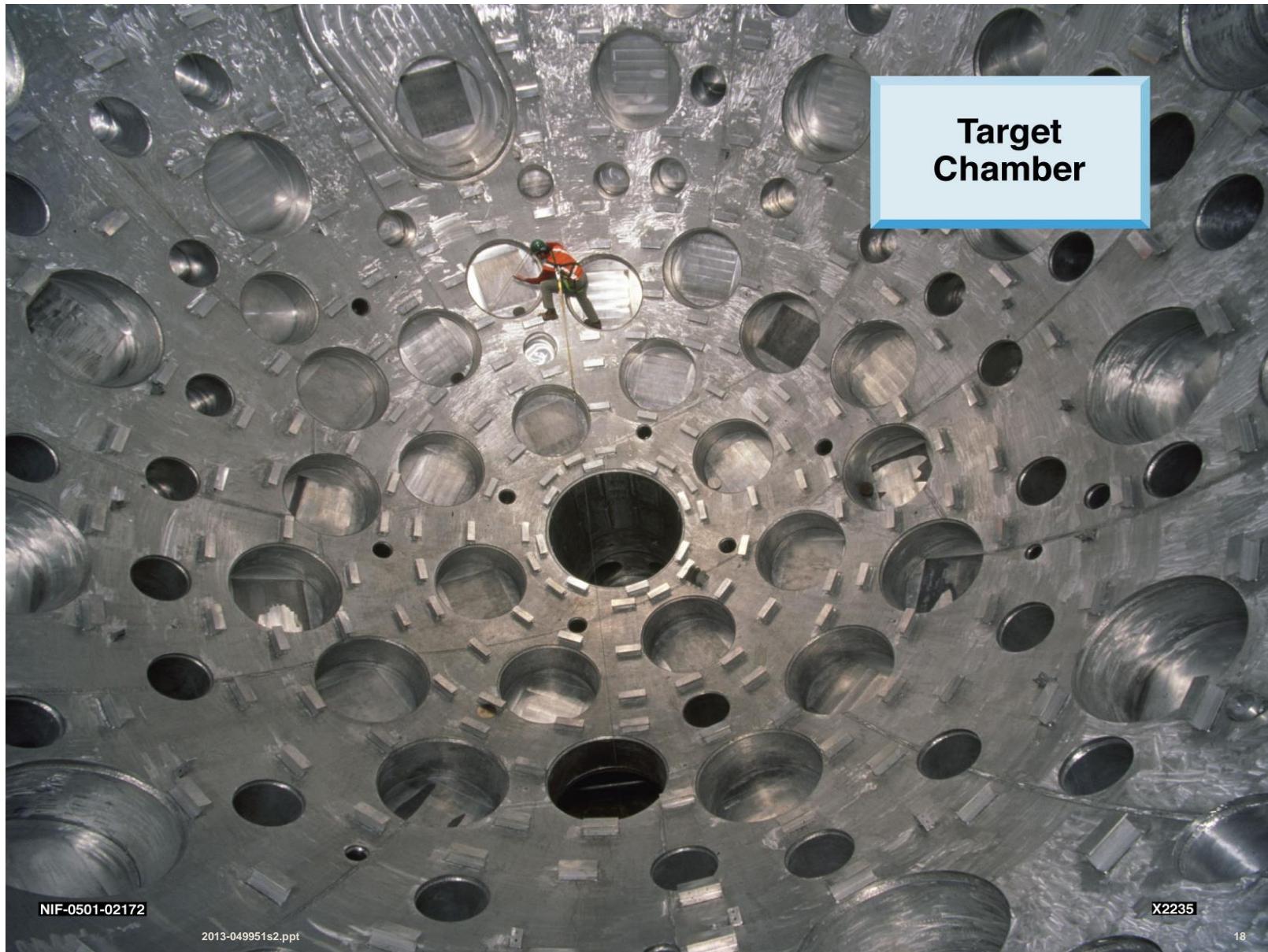
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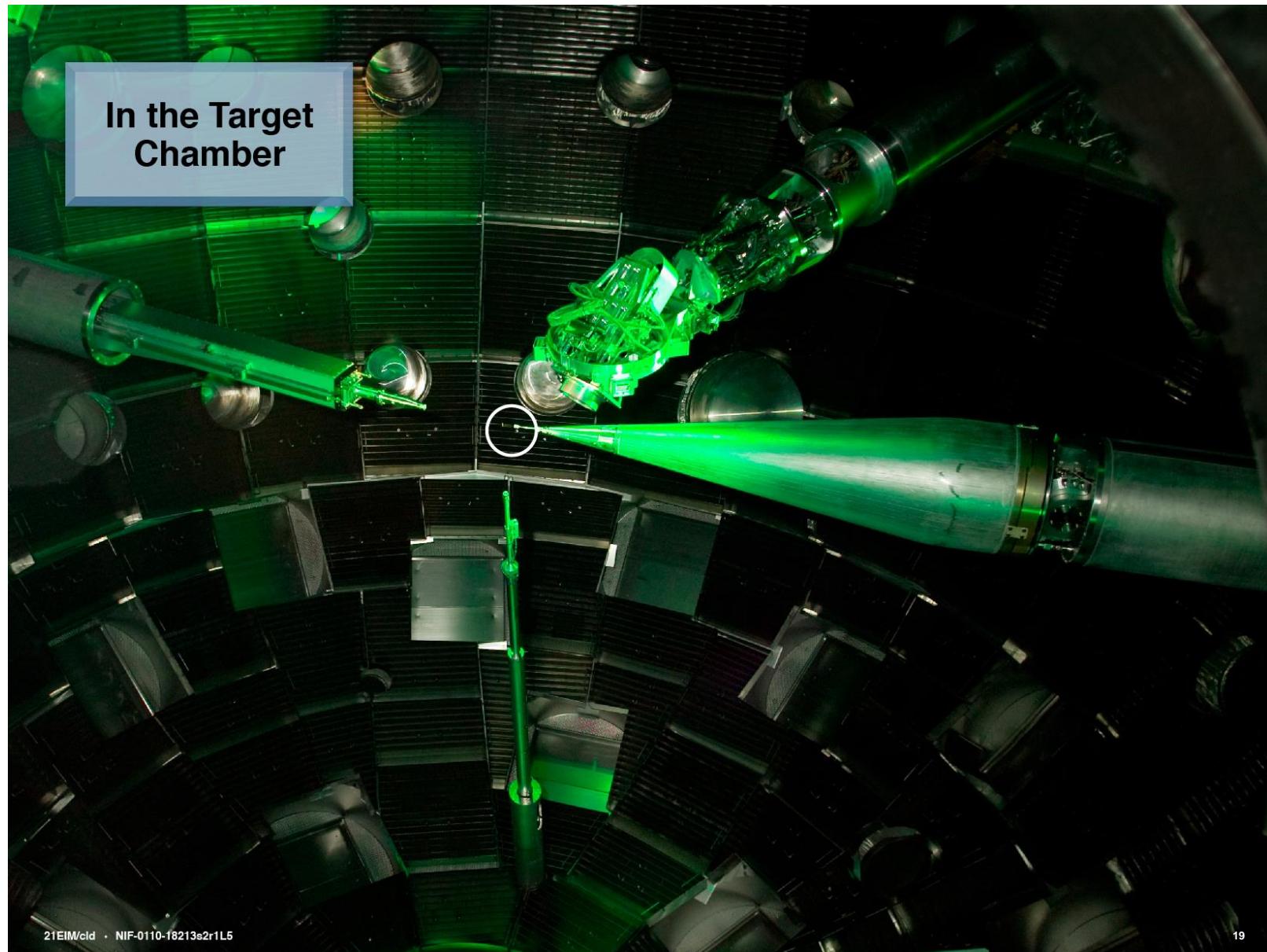


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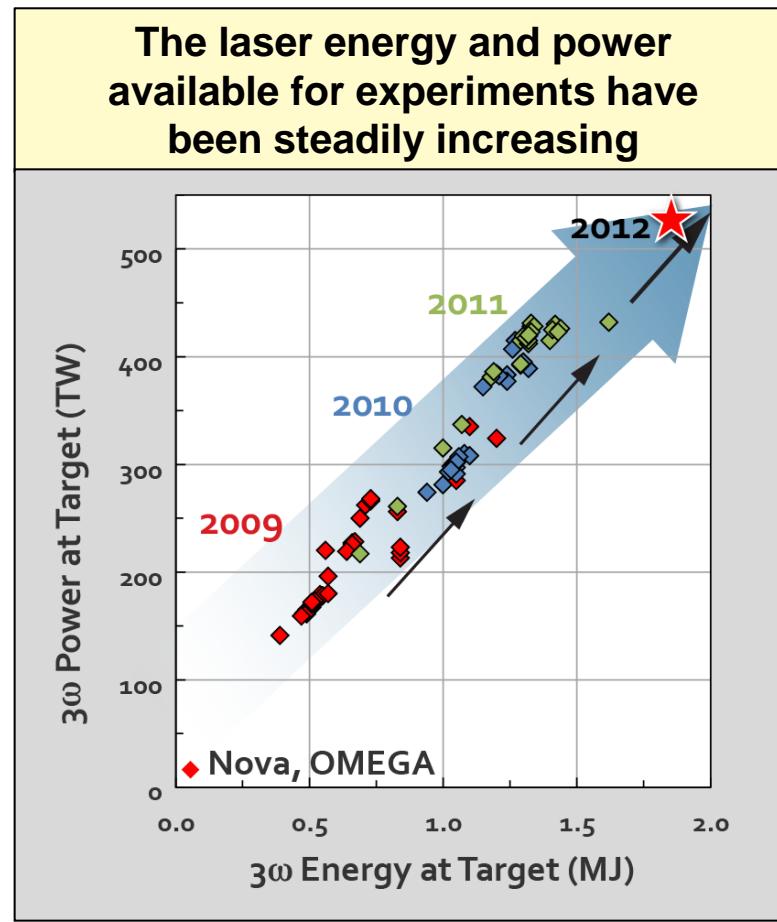
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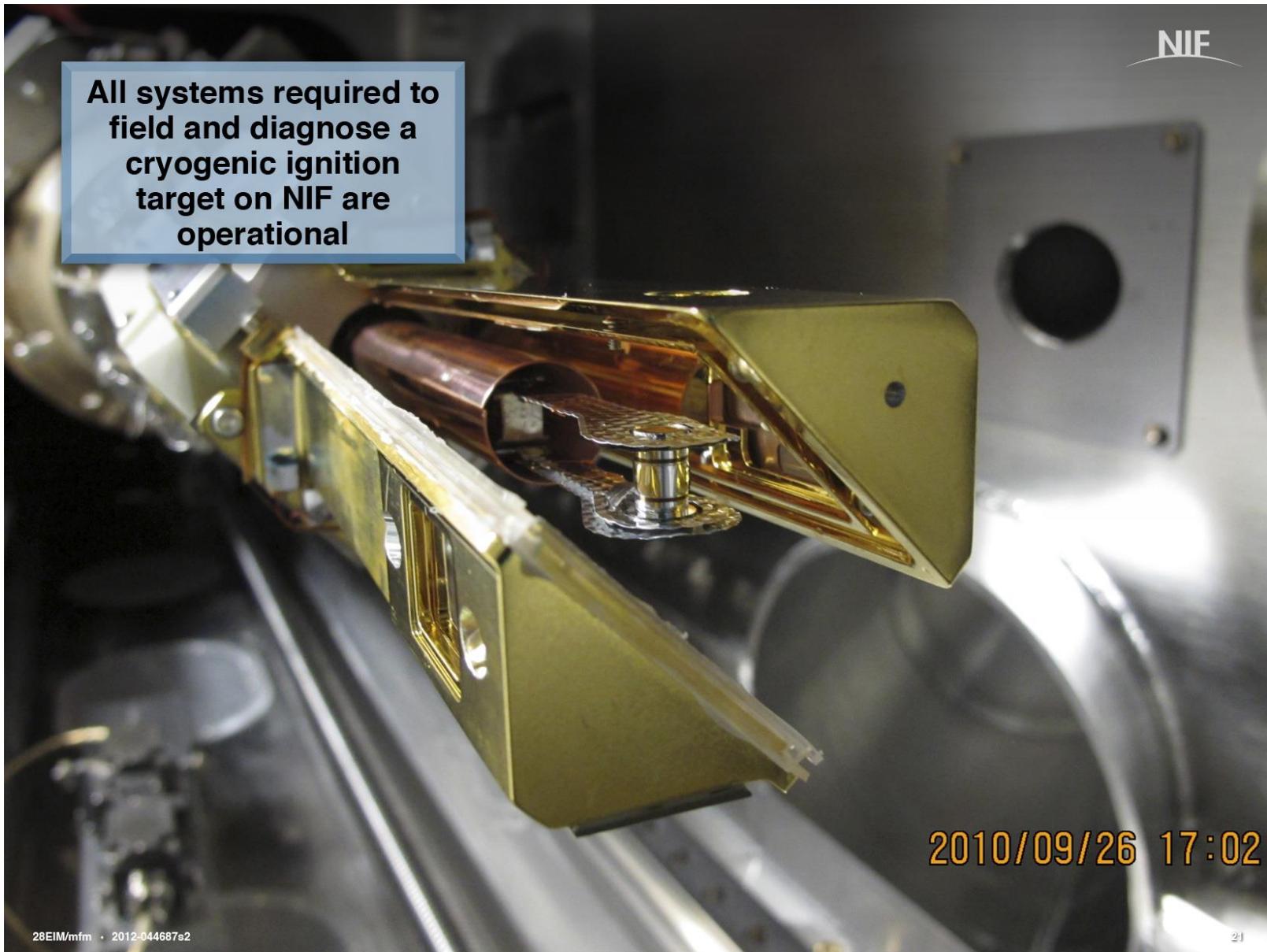


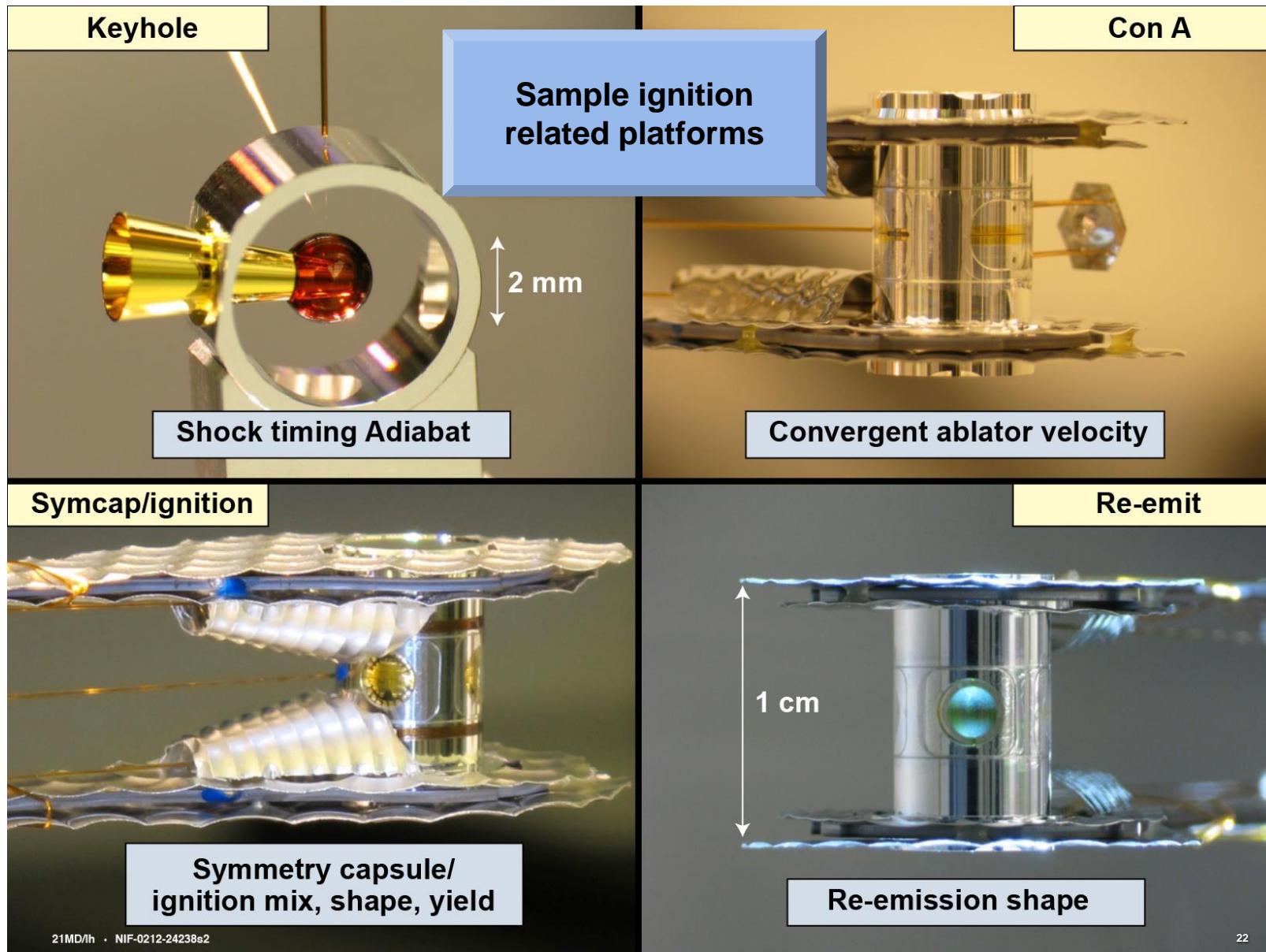
## NIF has met—and exceeded—its 1.8 MJ, 500 TW design specification

- NIF Laser is operating 24/7 with exceptional reproducibility and reliability (99%)
- The NIF has intrinsic capability to continue on this growth path for several more years

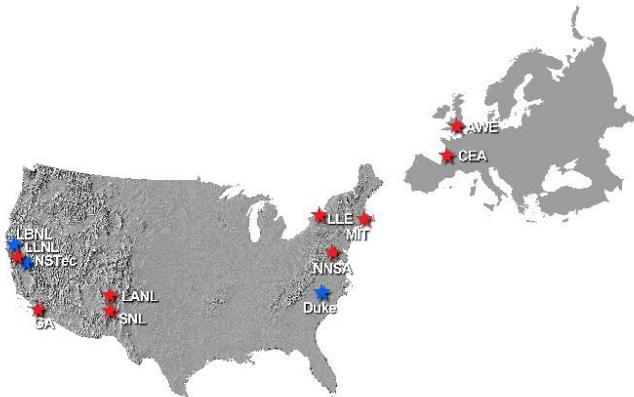


All systems required to  
field and diagnose a  
cryogenic ignition  
target on NIF are  
operational

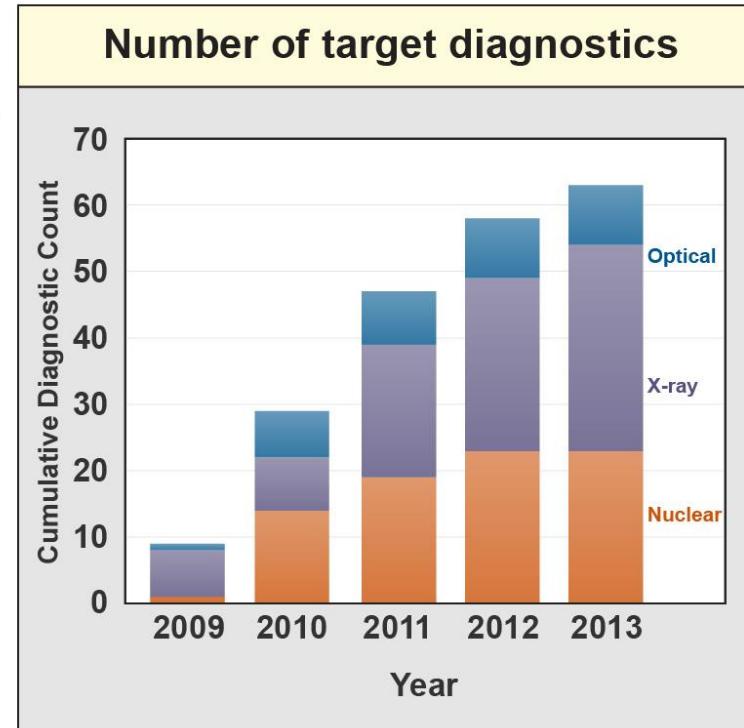


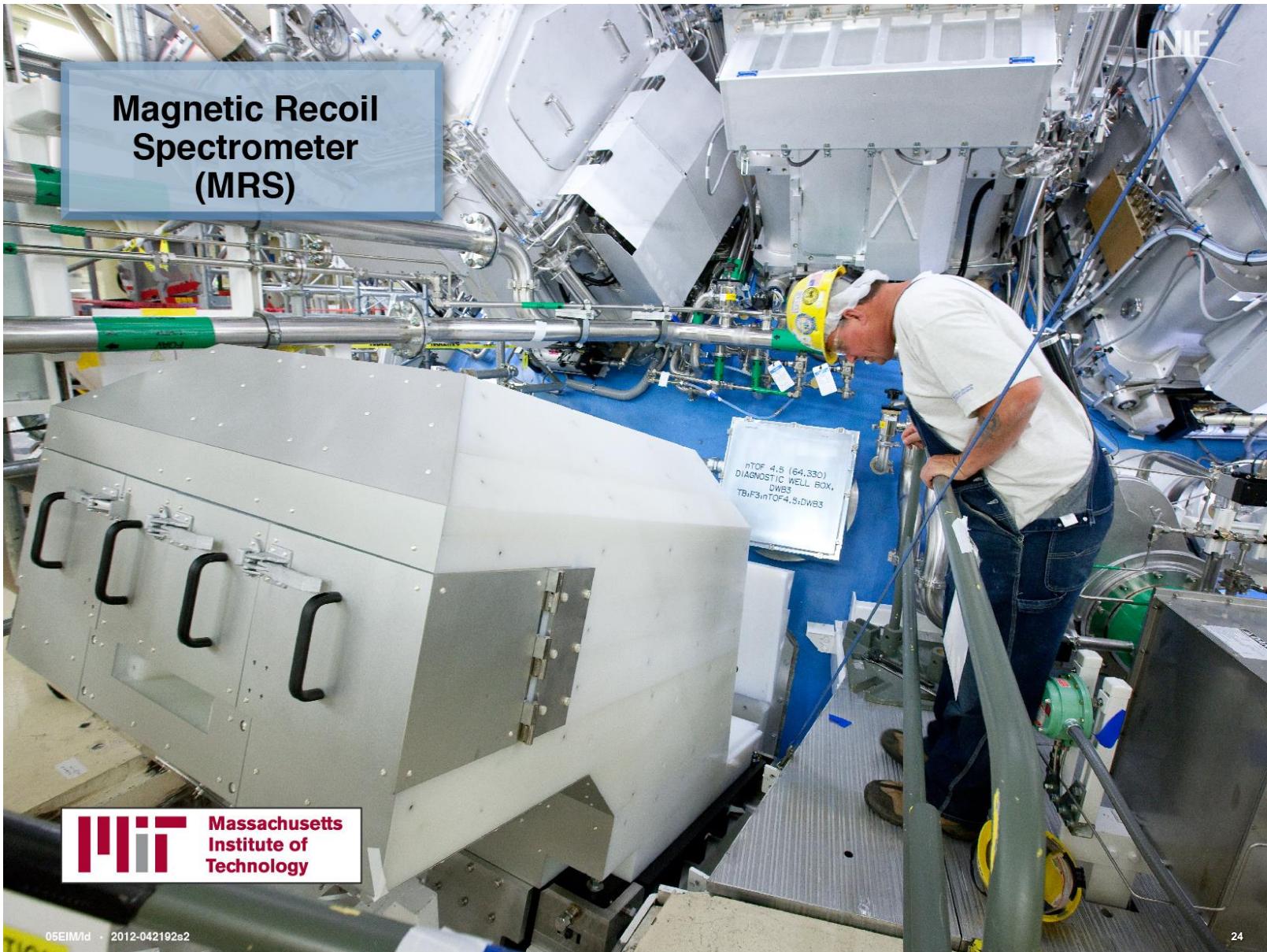


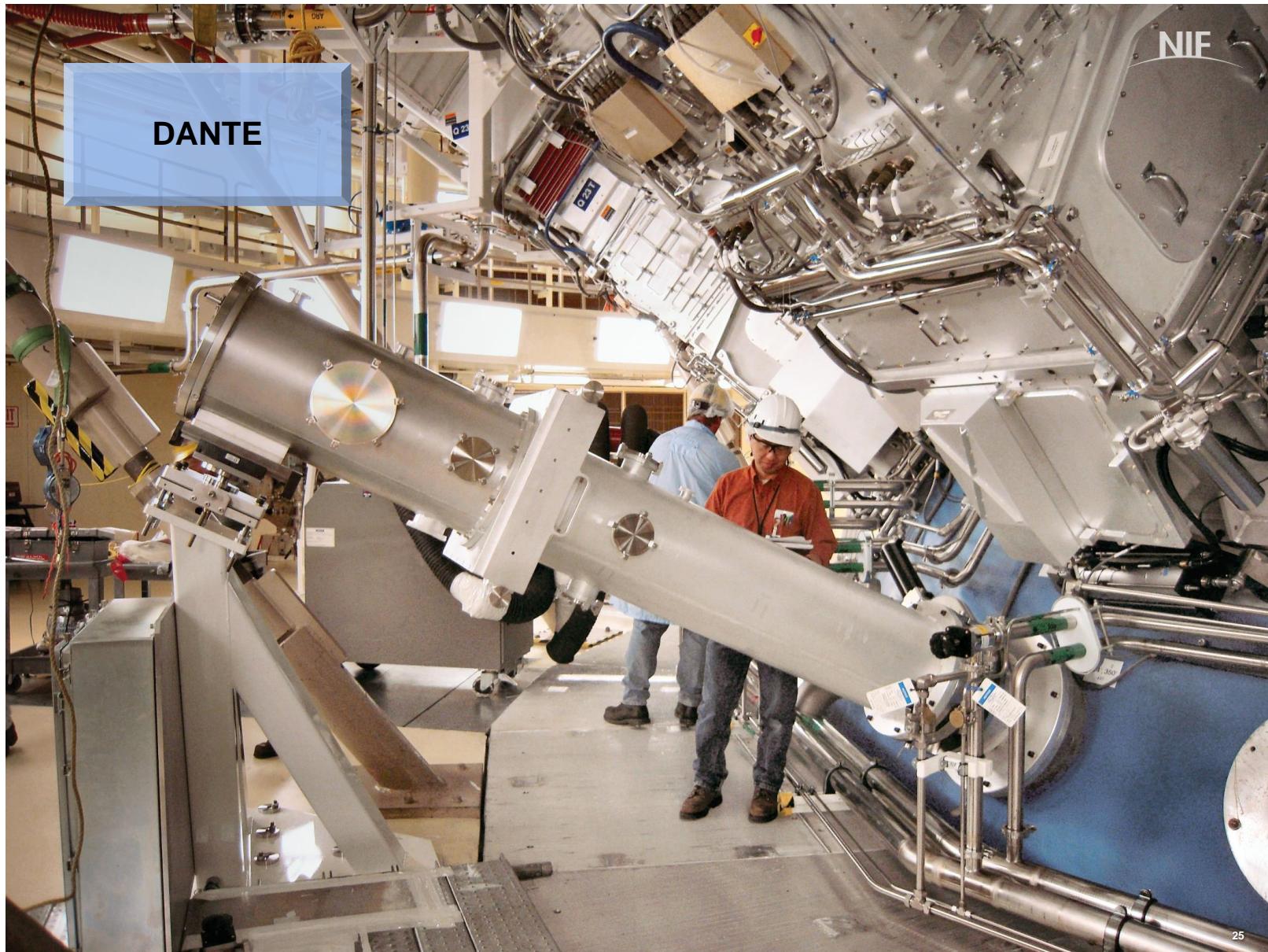
## 63 target diagnostics enable cutting edge science on the NIF



- LLNL
- MIT
- LANL
- CEA
- LLE
- Duke
- NSTec
- SNL
- U of M
- GSI
- LBNL
- AWE







# Gamma Reaction History (GRH)



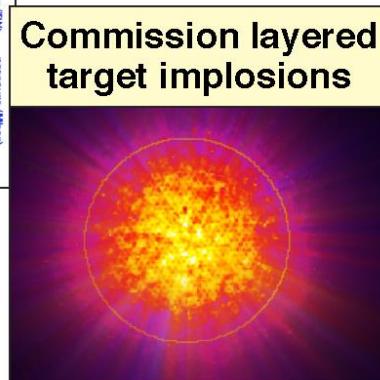
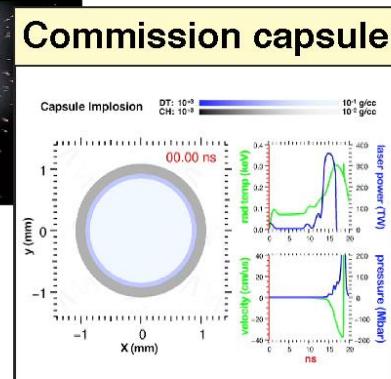
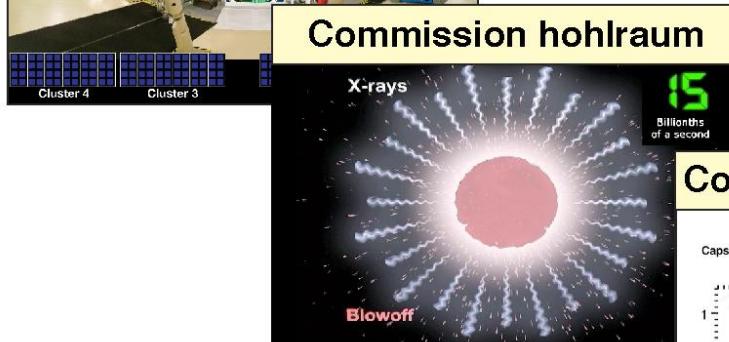




## Four steps to ignition



We are taking a systematic approach to learning and improving our engineering design to achieve ignition



## Highlights of progress towards ignition



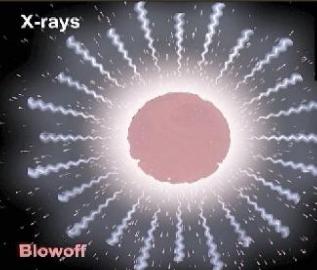
1.855 MJ

523 TW

300:1 contrast



X-rays

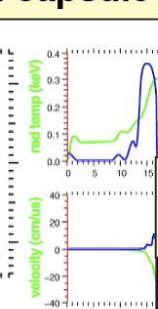
15  
Billions  
of a second

330 eV

~85% absorbed energy



**Commission capsule**



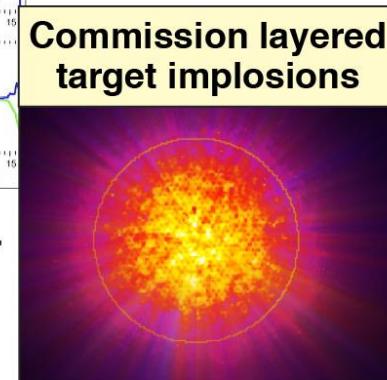
Convergence ratio ~35,  
 $\rho R \sim 1.3 \text{ gm/cm}^2$  (85% of requirement)  
 $V_{\text{implosion}} \sim 350 \text{ km/sec}$



Pressure ~150 GBar

 $\gamma \sim 9 \times 10^{14}$ 

**Commission layered target implosions**



## Highlights of progress towards ignition



1.855 MJ

523 TW

300:1 contrast



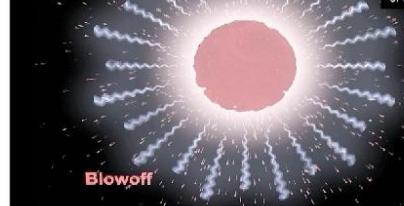
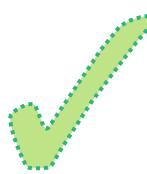
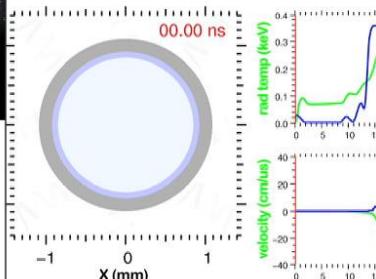
X-rays

15  
Billions  
of a second

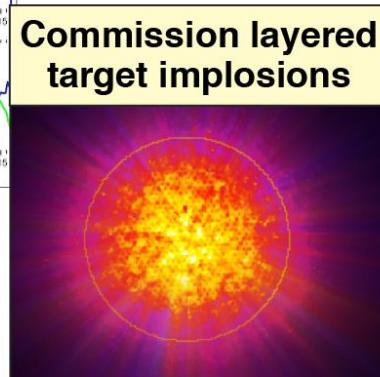
Blowoff

330 eV

~85% absorbed energy

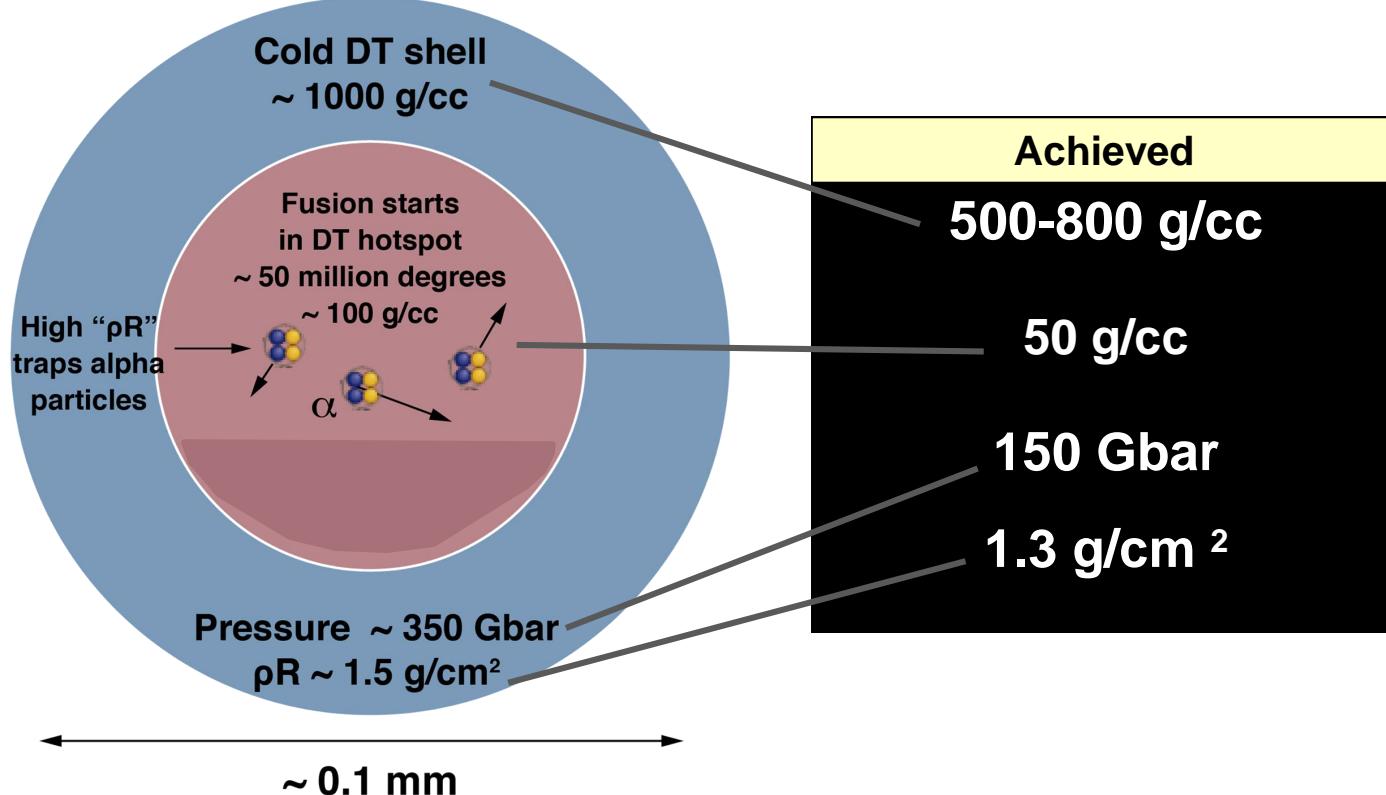
**Commission capsule**

Convergence ratio ~35,  
 $\rho R \sim 1.3 \text{ gm/cm}^2$  (85% of requirement)  
 $V_{\text{implosion}} \sim 350 \text{ km/sec}$

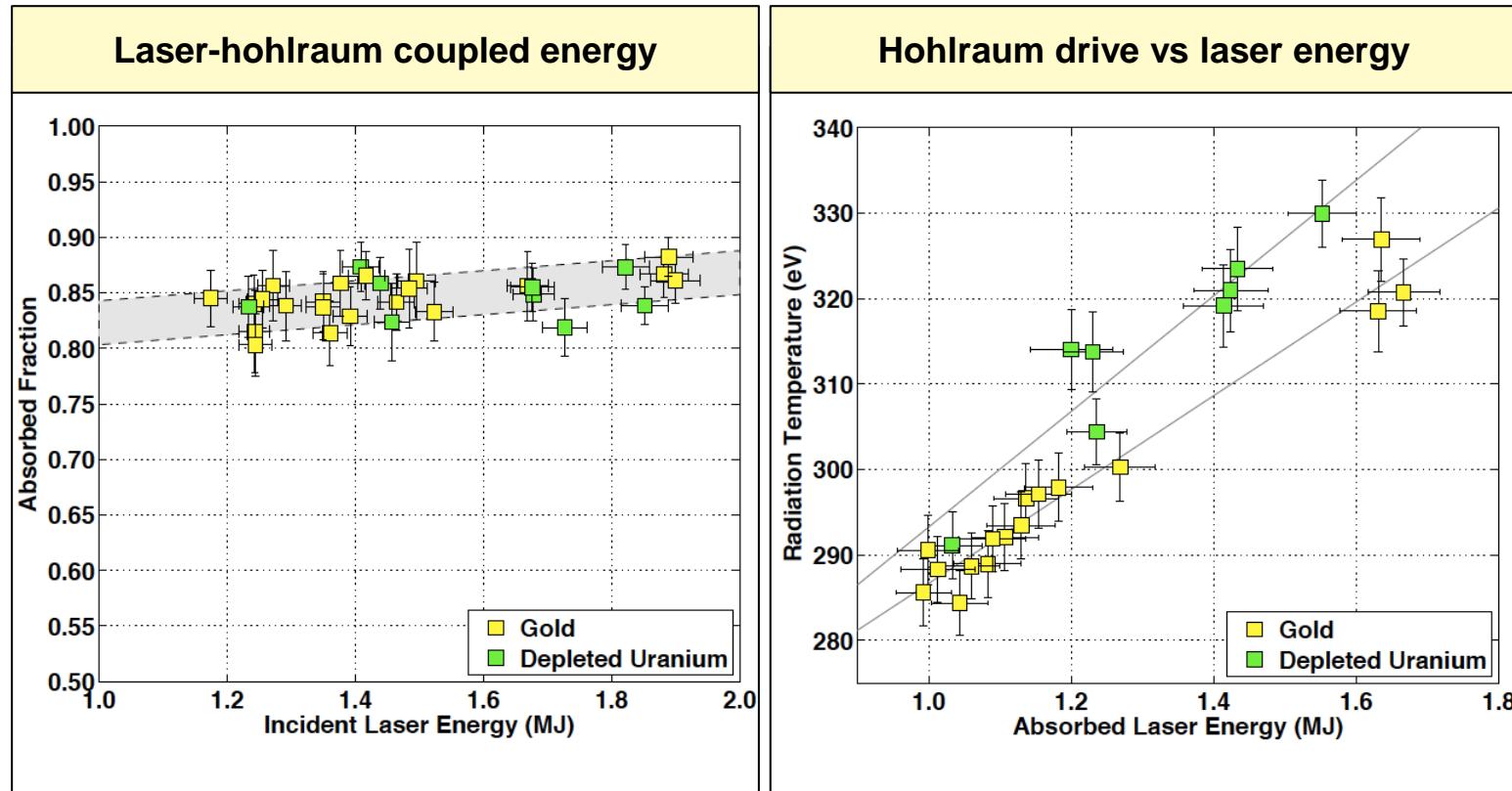
Pressure  $\sim 150 \text{ GBar}$  $\gamma \sim 9 \times 10^{14}$ **Commission layered target implosions**

## We have made good progress towards achieving ignition conditions on the NIF

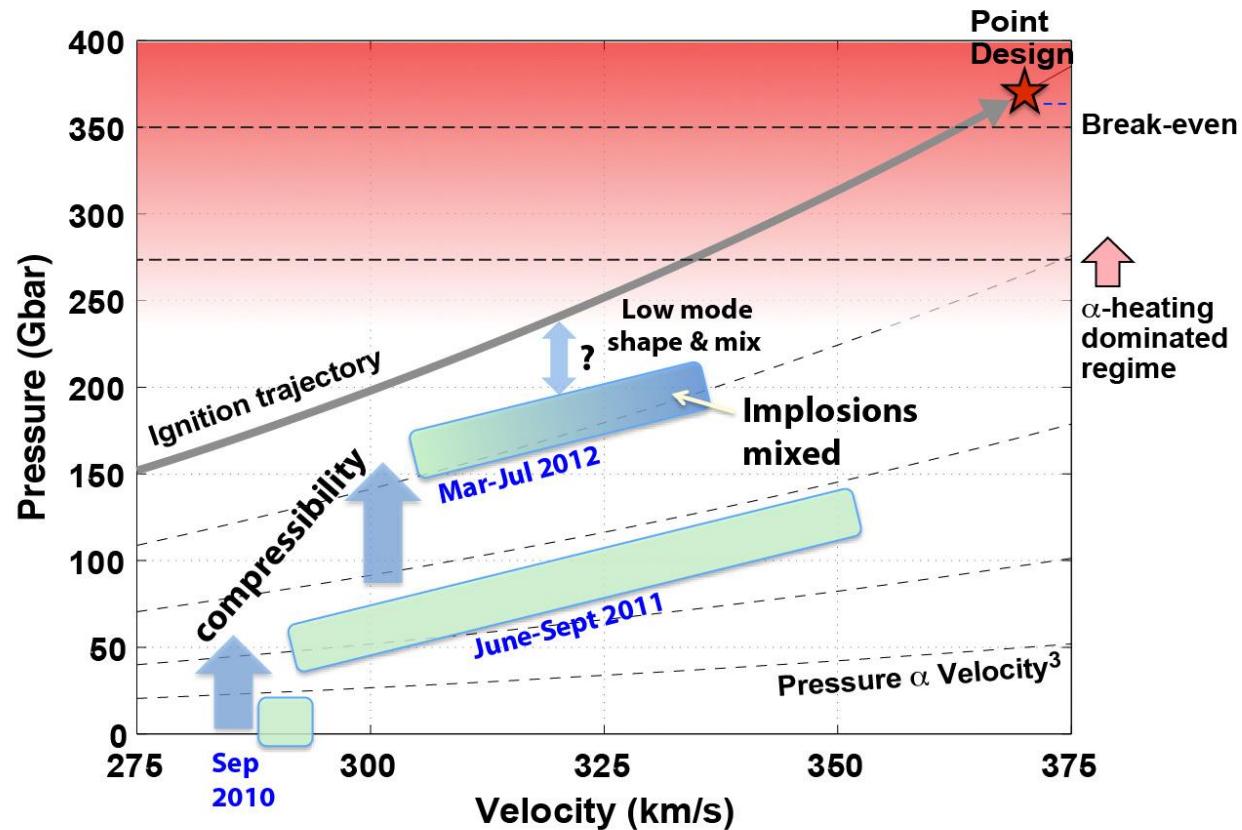
### Deuterium-Tritium (DT) fuel



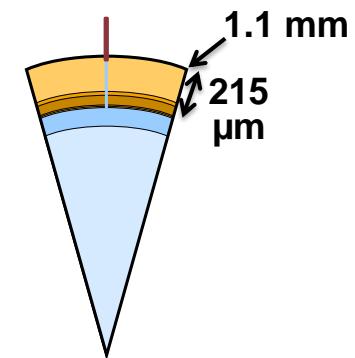
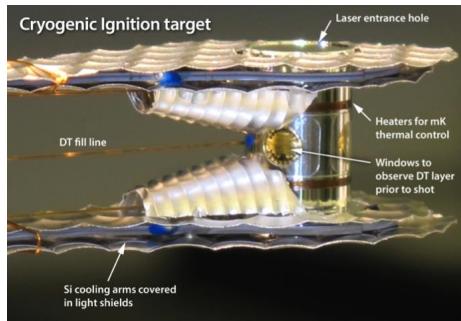
## Hohlraum physics- fraction of laser energy coupled is ~ 85%, and drive scales as expected



# Pressure and velocity in cryogenic layered implosions is approaching conditions required for ignition

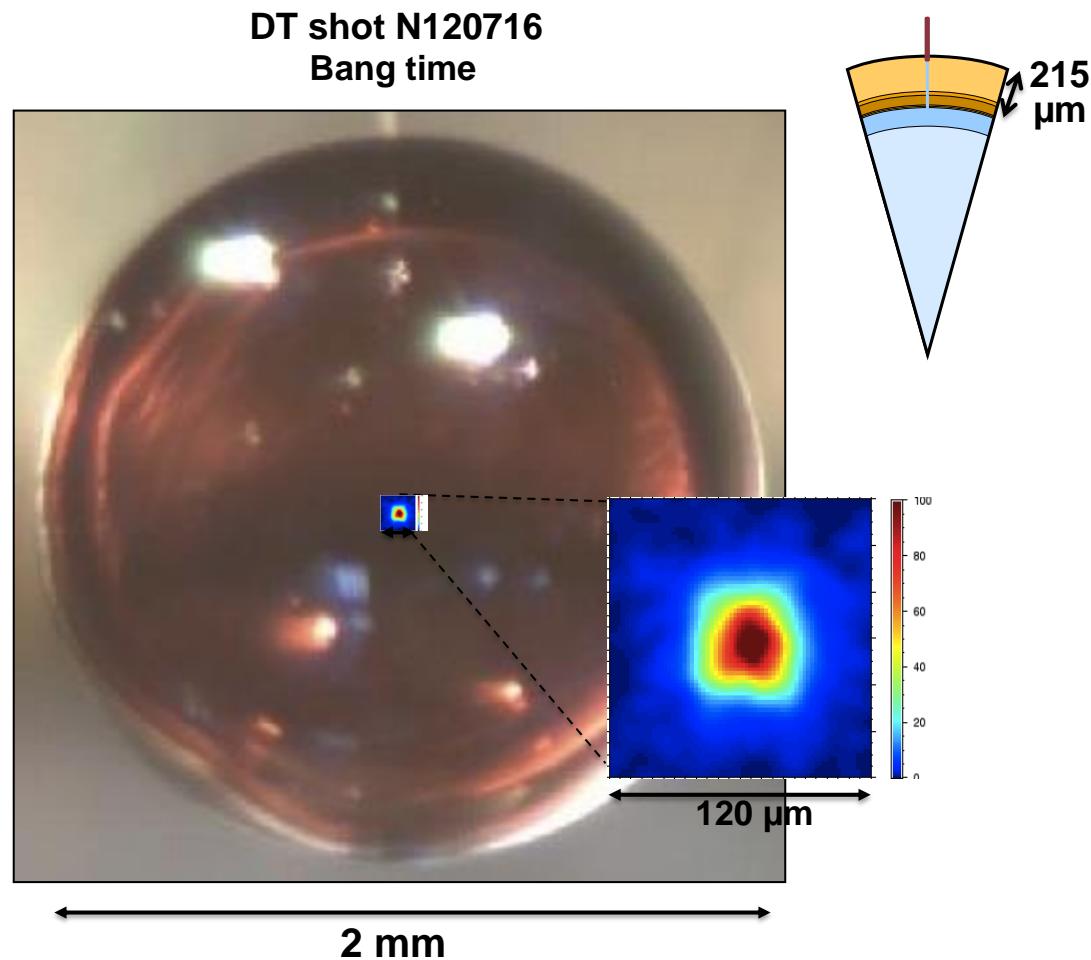


## The capsule starts at 2mm diameter

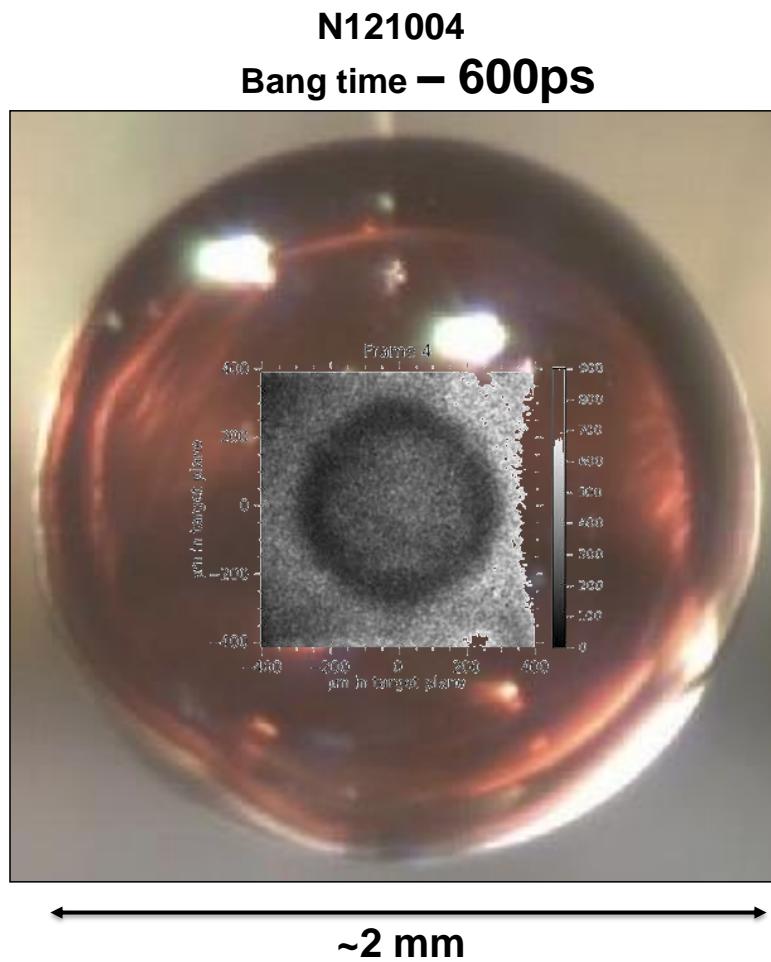


~2 mm

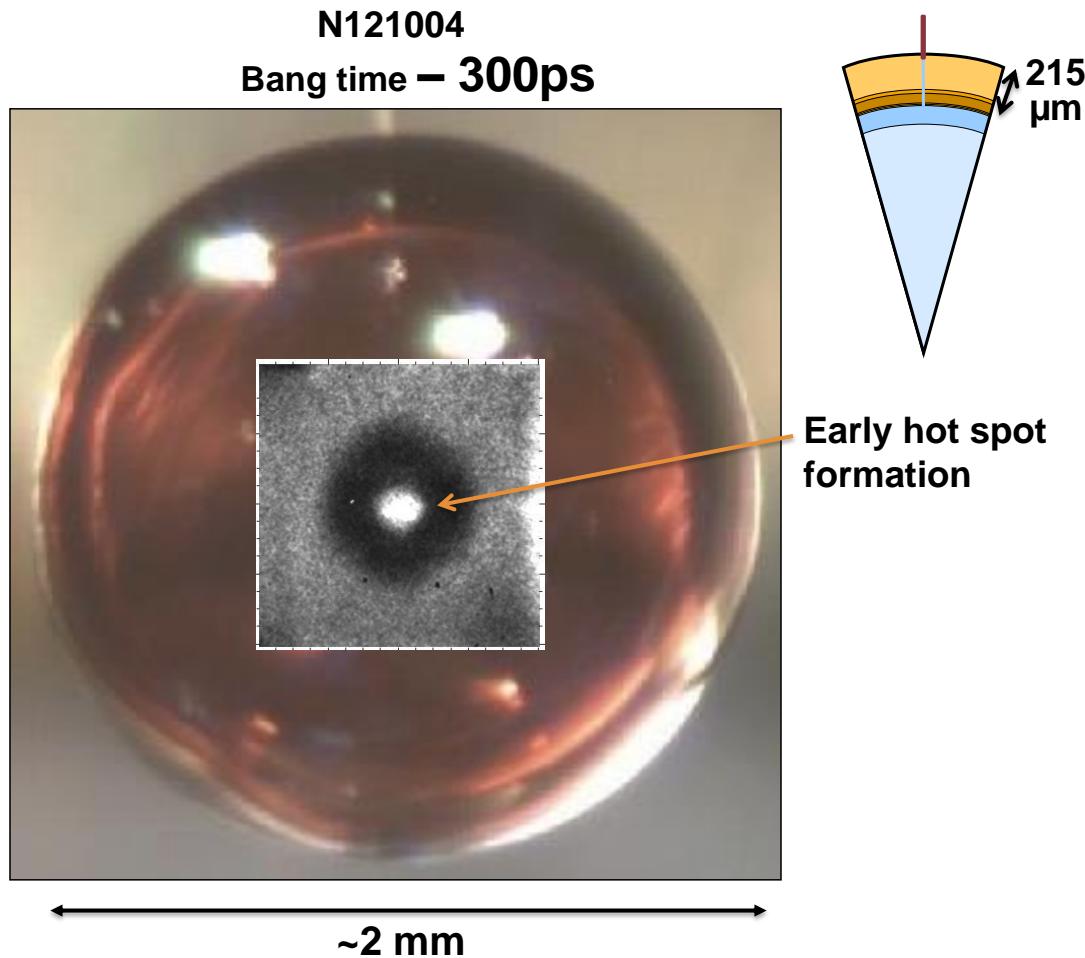
The hot spot viewed in x-ray emission looks quite round



## P4 “diamond” shape clearly seen during the implosion



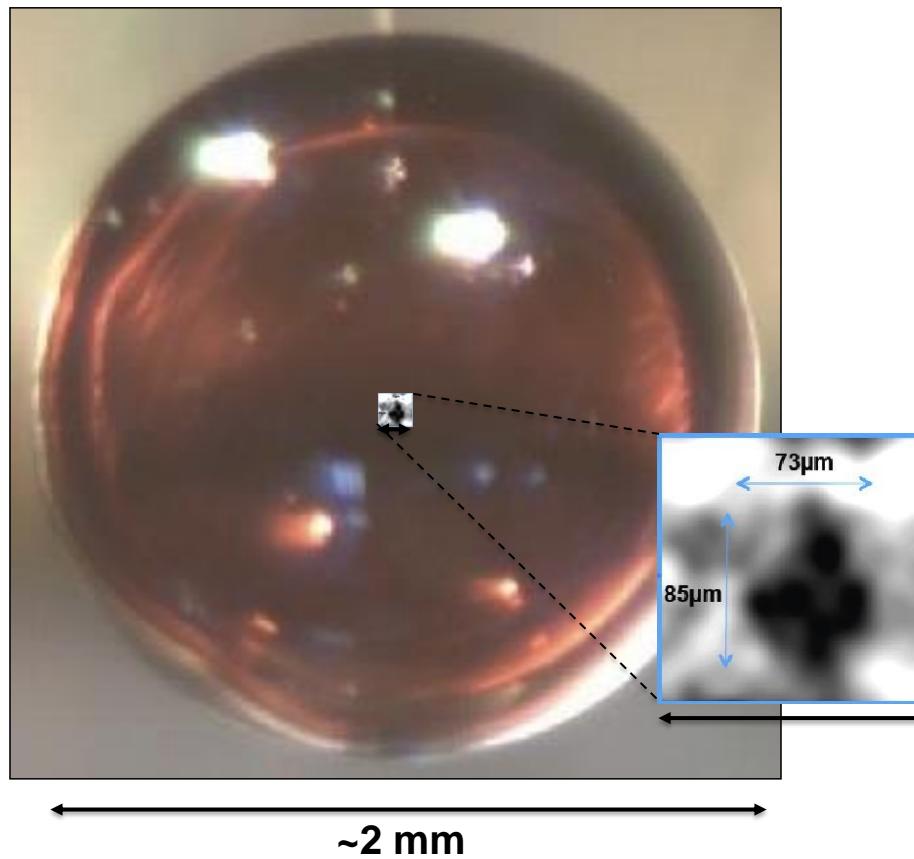
## P4 “diamond” shape clearly seen during the implosion



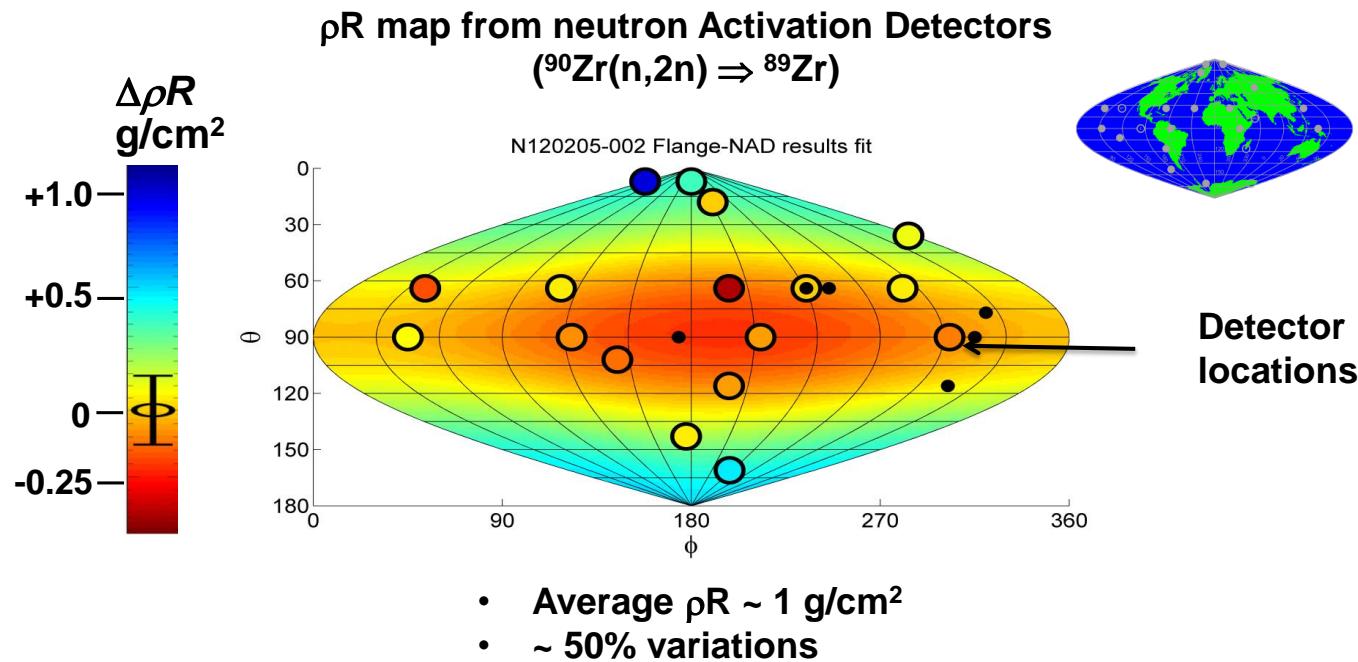
## Compton radiography for stagnated fuel: Promising results but improvements needed

N121005

Bang time



# Significant fuel $\rho R$ asymmetry measured by neutron activation detectors (FNADS)

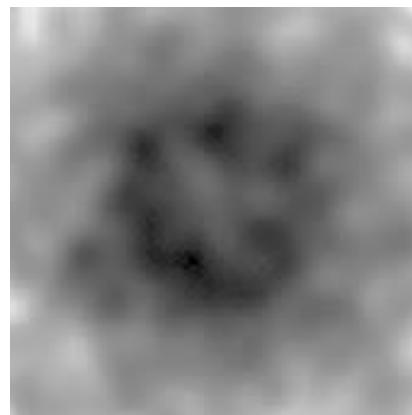


Motivates new 2D backlit imaging of the implosion  
Motivates Compton radiography for stagnated fuel shape

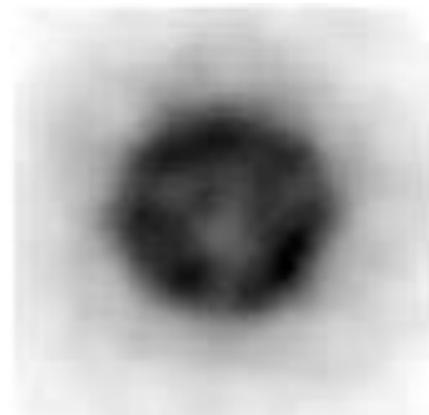
## NIF Advanced Radiographic Capability (ARC) is needed to diagnose evolution of cold fuel shape

Predicted synthetic images of stagnated DT fuel  
Requires 50-100 keV X-rays

3w NIF  
without ARC

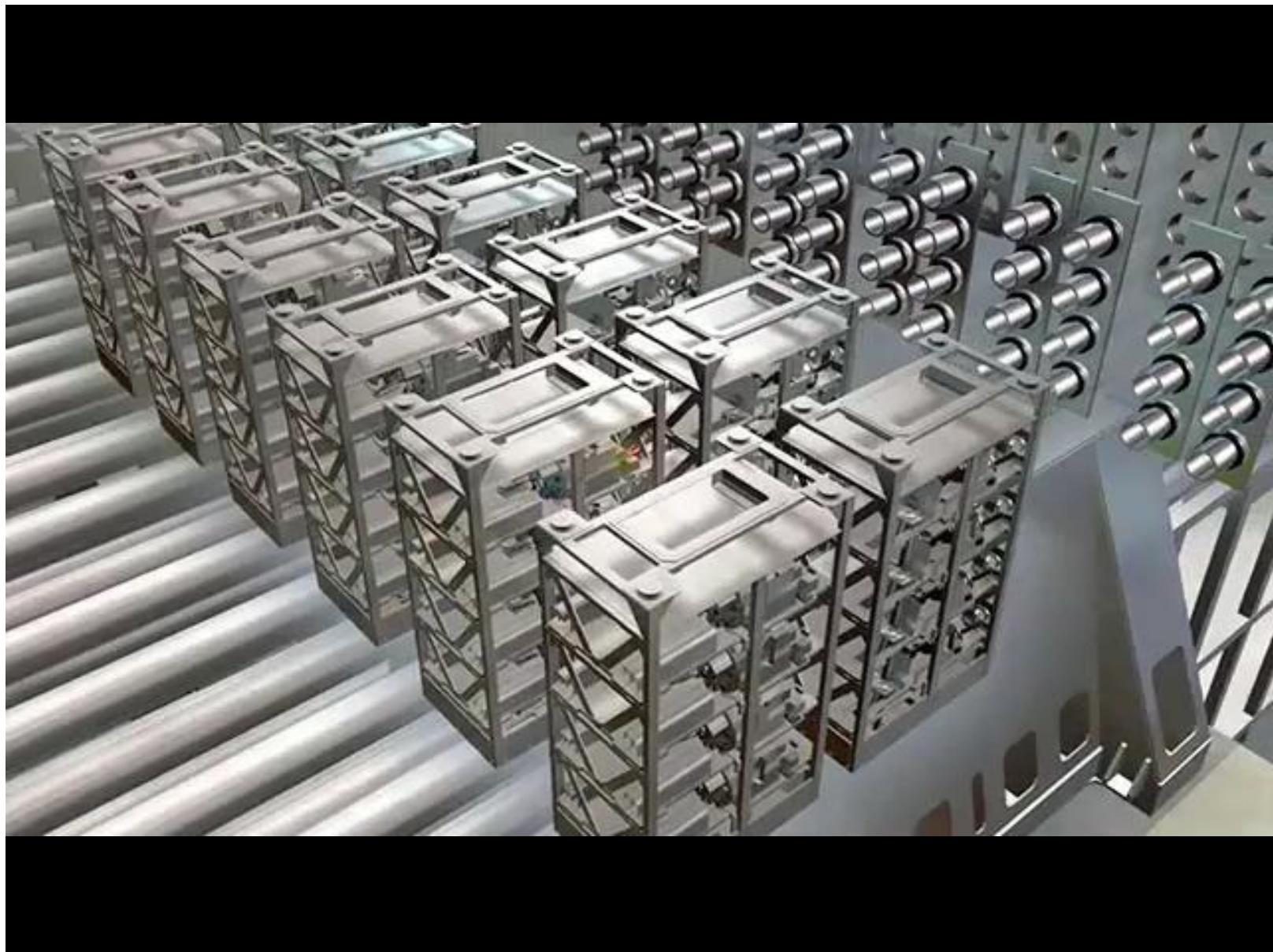


ARC



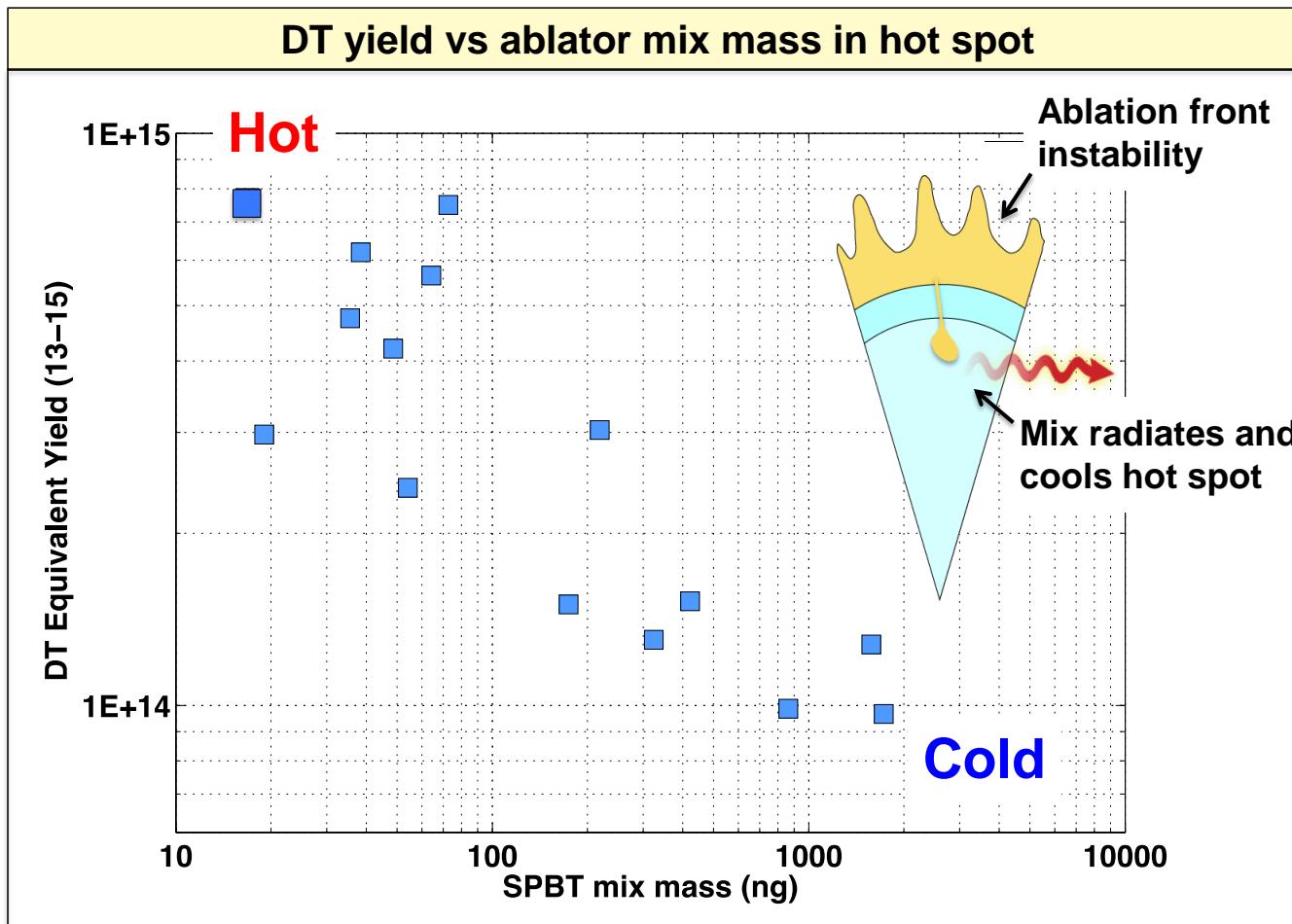
↔  
~ 100  $\mu\text{m}$

ARC estimated accuracy in fuel  $\rho R$  ~ 5-10% over ~ 10  $\mu\text{m}$  resolution element

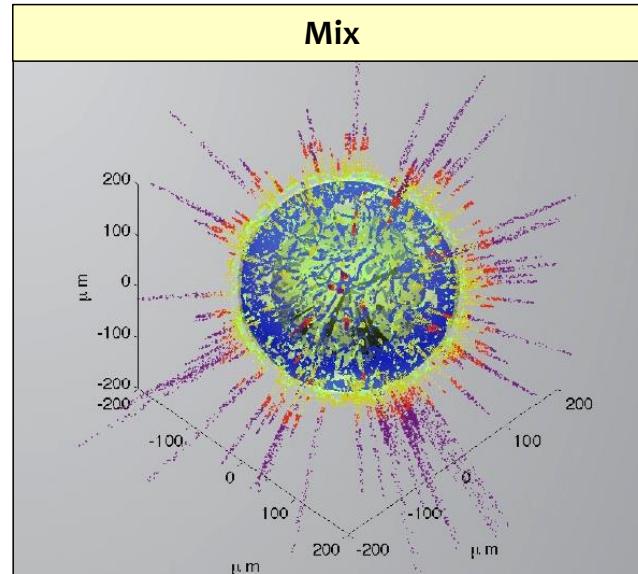
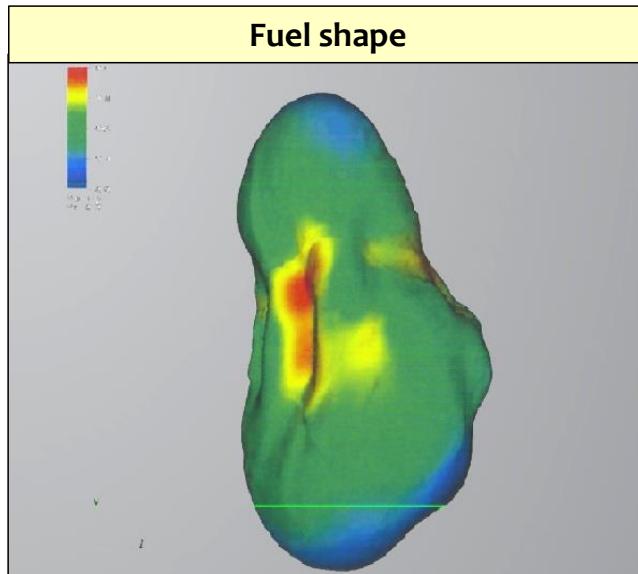


1532

Yield correlates strongly with hot spot mix-ablation front instability growth appears to be the issue



## The principal issues on ignition performance deficit



- Performance deficit likely due to combination of low mode X-ray drive asymmetry/cold fuel shape, and higher than simulated hydrodynamic instability

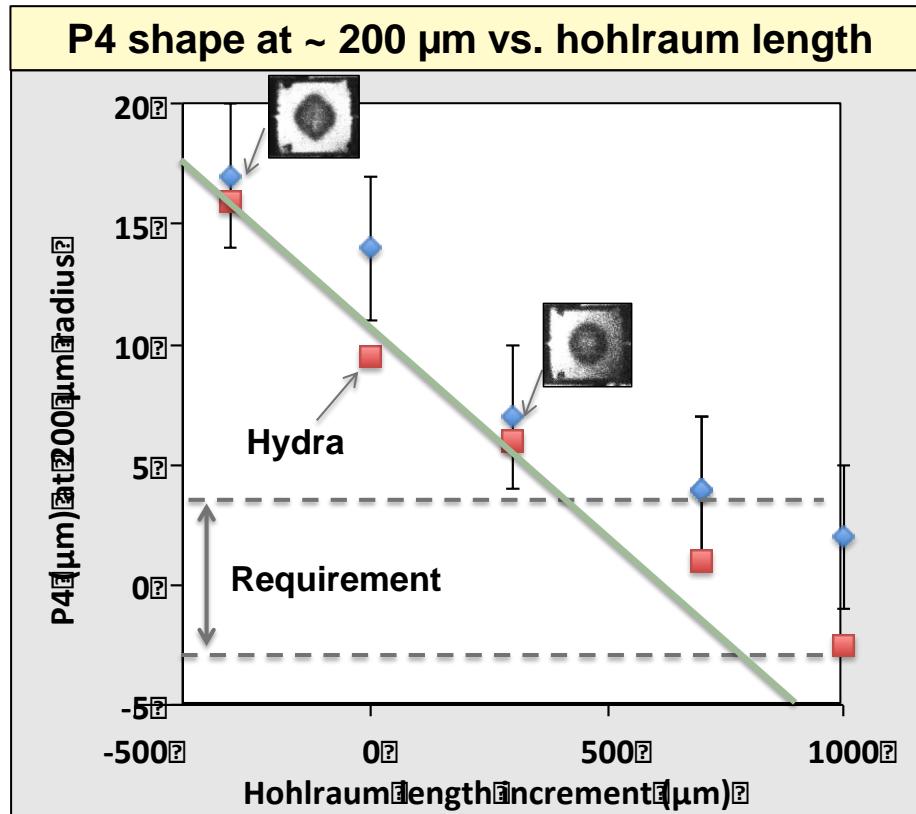
Identifying the reasons for the deficit in pressure/performance and developing mitigation strategies is a key element of the go-forward experimental plan

## NIF continues to make good progress towards achieving the conditions necessary for ignition

- The NIF laser and targets have met the highly demanding specifications for accuracy and control required by the ignition point design (Rev5)
- The hohlraum X-ray drive exceeded the ignition goal of 300eV accelerating implosions up to ~ 350 km/s (goal 370 km/s)
- Fuel  $\rho R$  up to 1.3 g/cm<sup>2</sup> were achieved (1.5 g/cm<sup>2</sup> goal)
- Nuclear yields are ~ 3-10X from alpha dominated regime
  - hotspot densities, pressures are ~ 2-3X lower than predicted/required
- Performance deficit likely due to combination of low mode X-ray drive asymmetry/cold fuel shape, and higher than simulated hydrodynamic instability

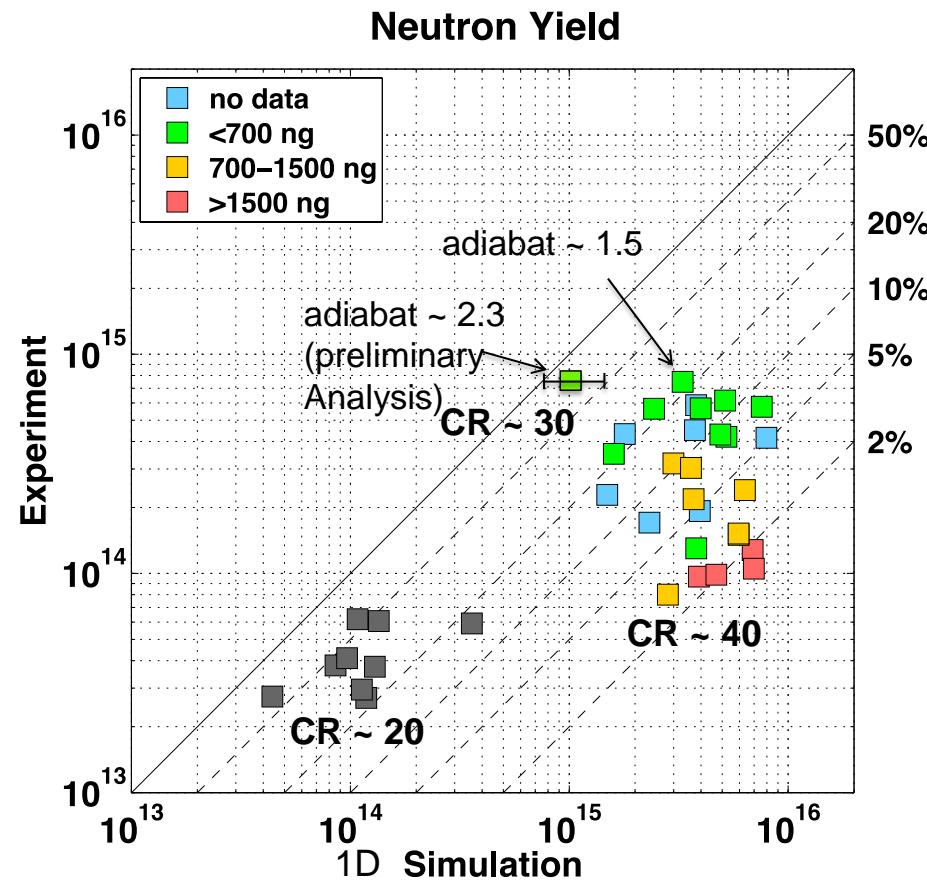
Good progress is being made in developing new experimental capabilities to identify the key reasons for the deficit in hot spot density, pressure and yield

Recent data show that P4 asymmetry can be modified by extending the hohlraum length



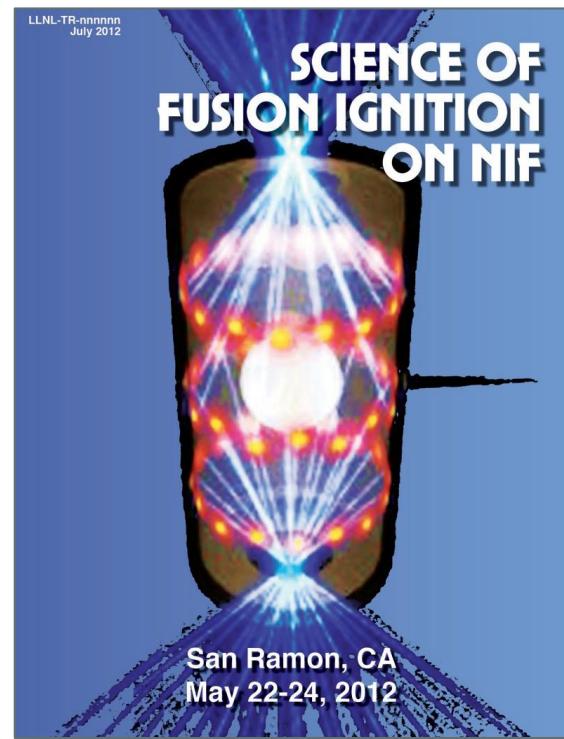
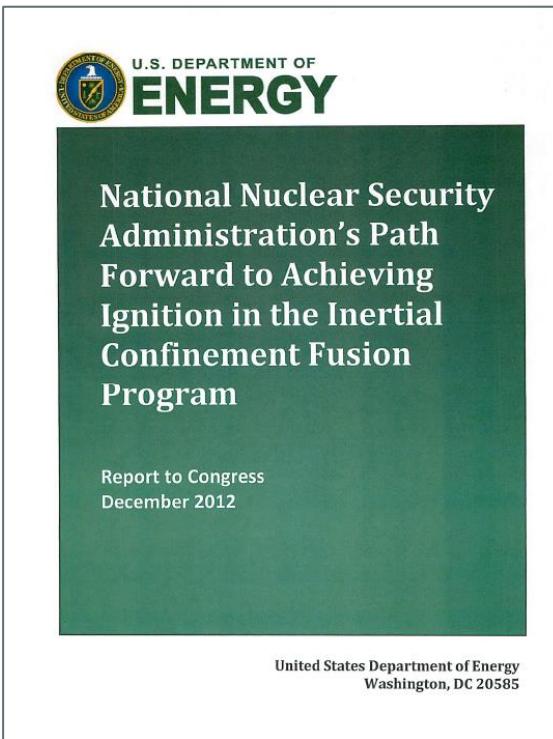
Time dependence of P4 symmetry remains an important question

# Higher adiabat DT layered implosion performs closer to 1D



The principal issues and go-forward strategy were summarized in a Dec. 2012 NNSA report to Congress and the Science of Fusion Ignition Workshop Report

NIF



We welcome and encourage the broader scientific community to engage  
In the ignition science program



## Fundamental science on NIF was addressed most recently in a 2011 NNSA/Office of Science report

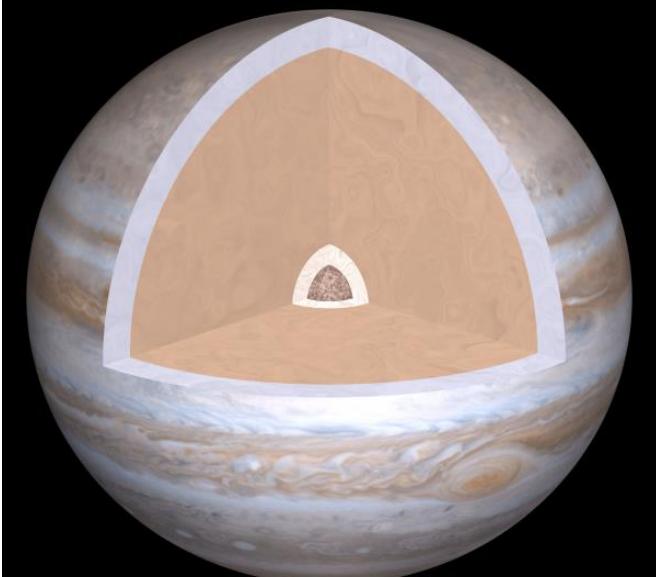


Summary of Workshop Priority Research Directions	
Panels	Priority Research Directions
1. Laboratory Astrophysics	1.1 Simulating Astrochemistry: The Origins and Evolution of Interstellar Dust and Prebiotic Molecules 1.2 Explanation for the Ubiquity and Properties of Cosmic Magnetic Fields and the Origin of Cosmic Rays 1.3 Radiative Hydrodynamics of Stellar Birth and Explosive Stellar Death 1.4 Atomic Physics of Ionized Plasmas
2. Nuclear Physics	2.1 Stellar and Big Bang Nucleosynthesis in Plasma Environments 2.2 Formation of the Heavy Elements and Role of Reactions on Excited Nuclear States 2.3 Atomic Physics of Ionized Plasmas
3. Materials at Extremes and Planetary Physics	3.1 Quantum Matter to Star Matter 3.2 Elements at Atomic Pressures 3.3 Kilovolt Chemistry 3.4 Pathways to Extreme States 3.5 Exploring Planets at NIF
4. Beams and Plasma Physics	4.1 Formation of and Particle Acceleration in Collisionless Shocks 4.2 Active Control of the Flow of Radiation and Particles in HEDP 4.3 Ultraintense Beam Generation and Transport in HED Plasma 4.4 Complex Plasma States in Extreme Laser Fields



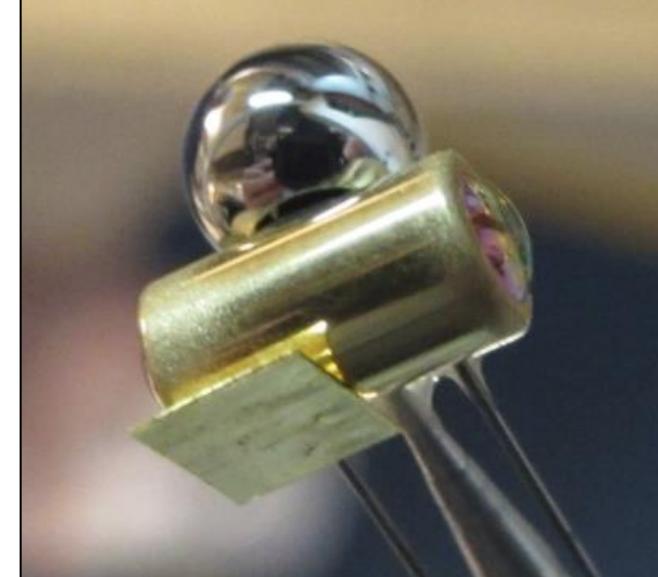
## NIF fundamental science program started in FY2009 via existing collaborations

**Equation of state/planetary interiors  
(UC Berkeley, Princeton, LLNL)**



**Examine EOS of compressed  
diamond, iron at pressures up to 50-  
100 MBar**

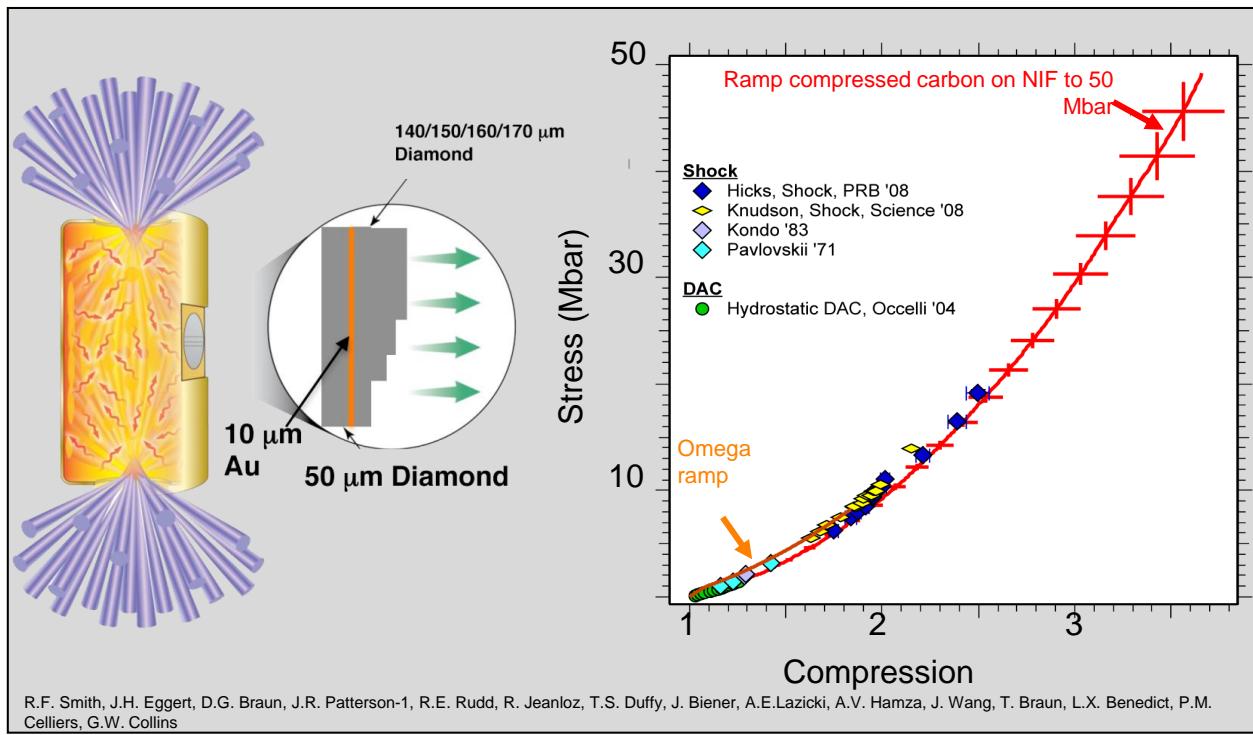
**Supernova hydrodynamics-  
radiative effects  
(Univ. of Michigan, LLNL)**



**Examine effects of radiation on  
growth of Rayleigh-Taylor  
instability**



NIF has been used to “shocklessly”  
compress carbon to 50 Mbar



Cal



NIF can now recreate the most extreme planetary core  
states in the solar system



# In a SQUEEZE

Elements under pressure reveal secrets of extreme chemistry

By Alexandra Witze

**B**ruce Banner isn't the only scientist who could crush you with one mighty squeeze. These days, the Hulk's superhuman strength is matched by researchers who squish all kinds of stuff in superscience experiments.

The goal isn't to save the world from baddies, but to explore new frontiers in the nature of matter. After all, most material in the universe exists at bone-crushing pressures. Think massive stars and planetary cores — realms no comic book fan or other Earth dweller has ever seen.

Deep within the planet, rock experiences pressures more than 1 million times as great as the "1 atmosphere" that ordinary humans live under at sea level. Pressures at the centers of ultradense neutron stars are some trillion quadrillion times greater. Under such extreme conditions, atoms themselves begin to buckle.

To mimic these hellish realms, scientists are ramping up pressure in the lab, like the Hulk getting ever stronger as he gets madder. In the process, they're squeezing out some surprising insights.

One team has found a new kind of iron oxide, a compound that somehow had never been seen before, even though it contains two of the most common elements in Earth's crust. Another group argues that hydrogen's odd behavior at high pressures means that the cores of giant gas planets, such as Jupiter, are eroding in a slow hydrogen drip. Meanwhile scientists at the National Ignition Facility in Livermore, Calif., have squeezed diamond to record pressures, uncovering unexpected and exotic behaviors.

Chemistry, it seems, is a different beast under high pressure. "We're developing a whole new paradigm for understand-

[www.sciencenews.org](http://www.sciencenews.org)

**"Meanwhile scientists at the National Ignition Facility in Livermore, Calif., have squeezed diamond to record pressures, uncovering unexpected and exotic behaviors."**



## NIF issued a call for proposals for fundamental science experiments in FY2010

### FY2010 Call for Proposals

**NIF**  
National Ignition Facility & Photon Science  
Bringing Star Power to Earth

News | About NIF & PS | Programs | For Users | Science & Technology | Multimedia | Education

Search NIF | Go | NIF Home > For Users > Call For Proposals > Concept Development | TEXT SIZE | + | -

**For Users**

- Call for Proposals
- Facility Time
- Concept Development
- Proposal Submission Form
- Experimental Capabilities
- Join the User Group

**Call for Proposals: High Energy Density Science Experiments at the NIF**

The National Ignition Facility (NIF) at Lawrence Livermore National Laboratory (LLNL) is a 192-beam laser system designed for research in inertial confinement fusion (ICF) and other areas of high energy density (HED) science. NIF was constructed by the US National Nuclear Security Administration (NNSA) in support of the US Stockpile Stewardship Program (SSP). NIF construction was completed on March 27, 2009. NIF is now operational and the most powerful ICF laser facility in the world.

LLNL is issuing a call for proposals for experiments in fundamental high energy density science for the period FY2010-FY2012. The

may apply for NIF facility direct financial support for available at this time, though the client with available

Applicants may apply for 100K to develop ideas for leverage existing NIF possible. This will provide an advance fundamental high

**Call for Proposals in two major areas:**

- Facility Time (44 letters of intent, 40 full proposals)**
- Concept Development (\$100k maximum 1 year awards, 42 proposals)**

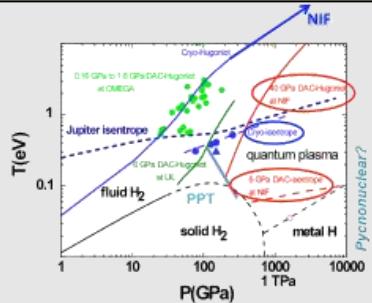


**NIF fundamental science call was the first general proposal issued by NIF and provided valuable insight and experience for implementing NIF governance in support of all missions**



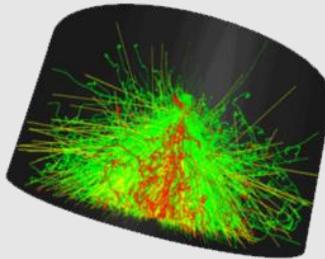
## Proposals selected in FY2010 call span an exciting spectrum of scientific questions

### Observing new states of matter (H)



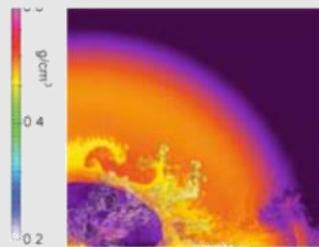
UC Berkeley, Carnegie Institution

### Understanding the most energetic events in the universe



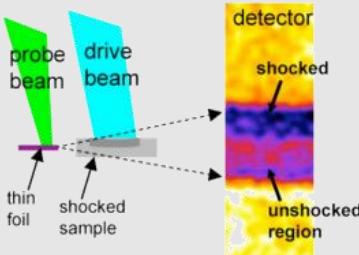
LLNL

### How do supernovae Explode?



Florida State University

### Probing the highest energy density states on Earth

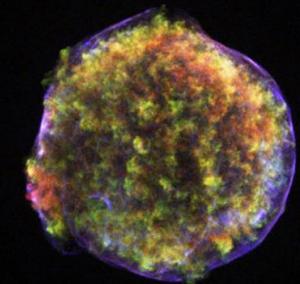


GSI/UC Berkeley



## Proposals selected in FY2010 call span an exciting spectrum of scientific questions (cont.)

### Origin of ultra-high energy cosmic rays



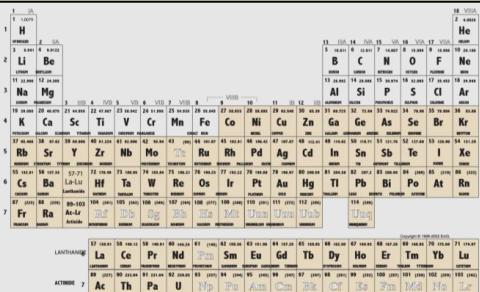
Osaka Univ./Oxford Univ.

### Large-scale behavior of matter in the universe



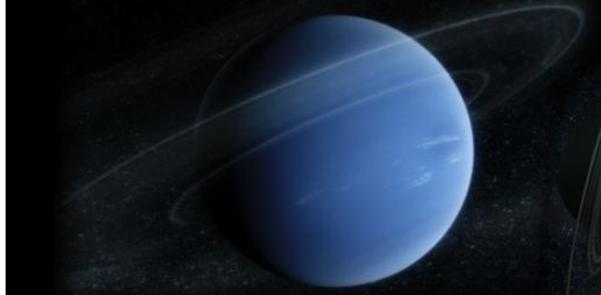
CEA/LLNL

### Synthesis of elements heavier than iron



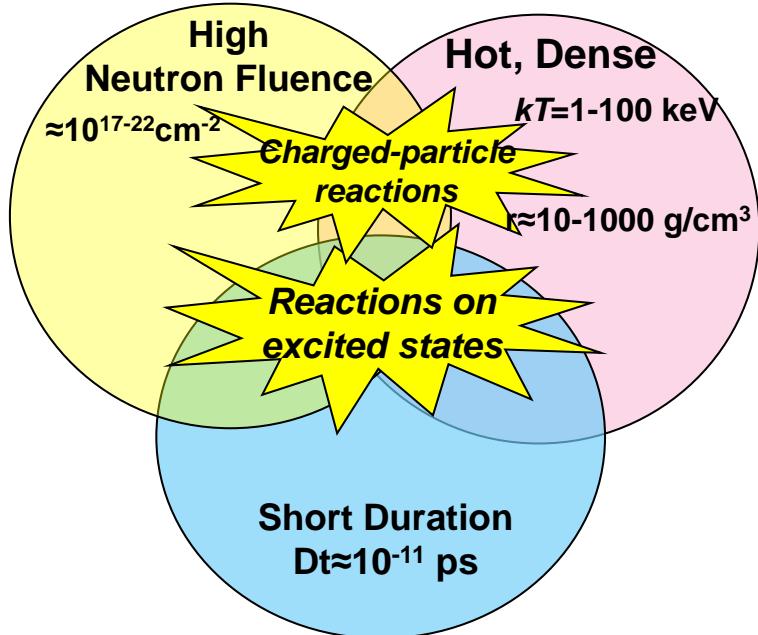
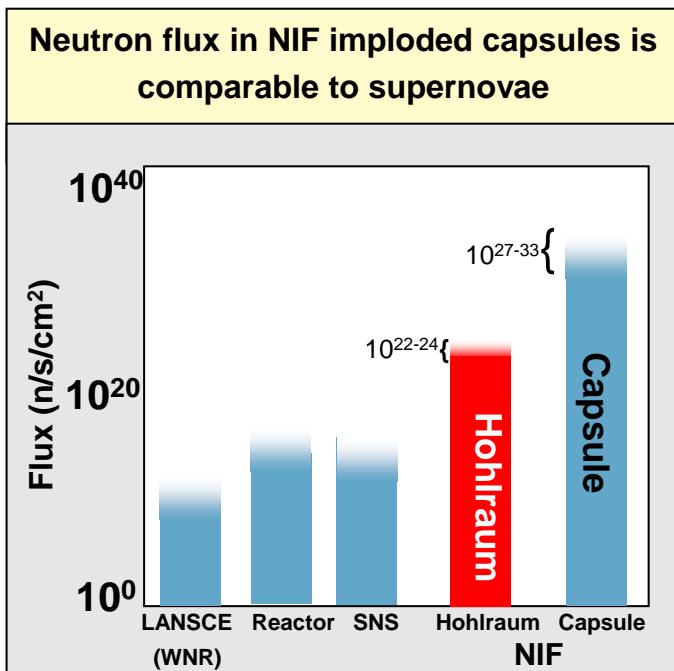
LLNL

### Novel phases of compressed diamond



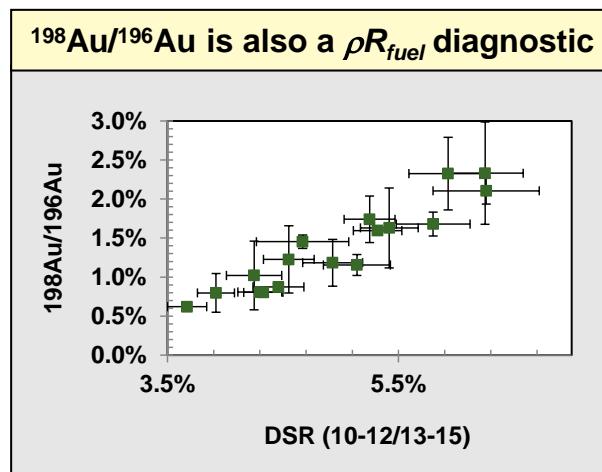
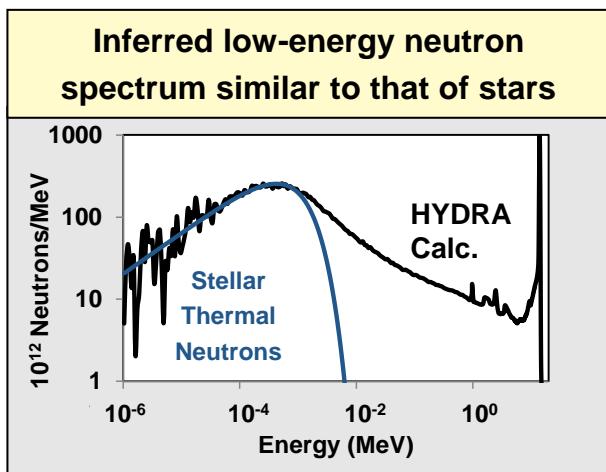
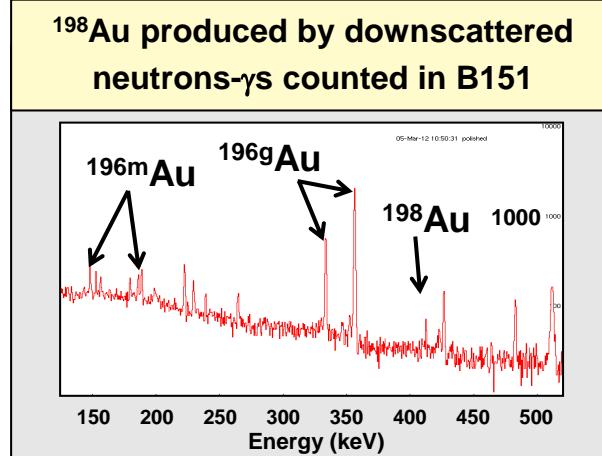
Oxford Univ./LLNL

## The high $e$ , $\gamma$ and n-flux in a NIF capsule might allow us to explore reactions on short-lived nuclear states

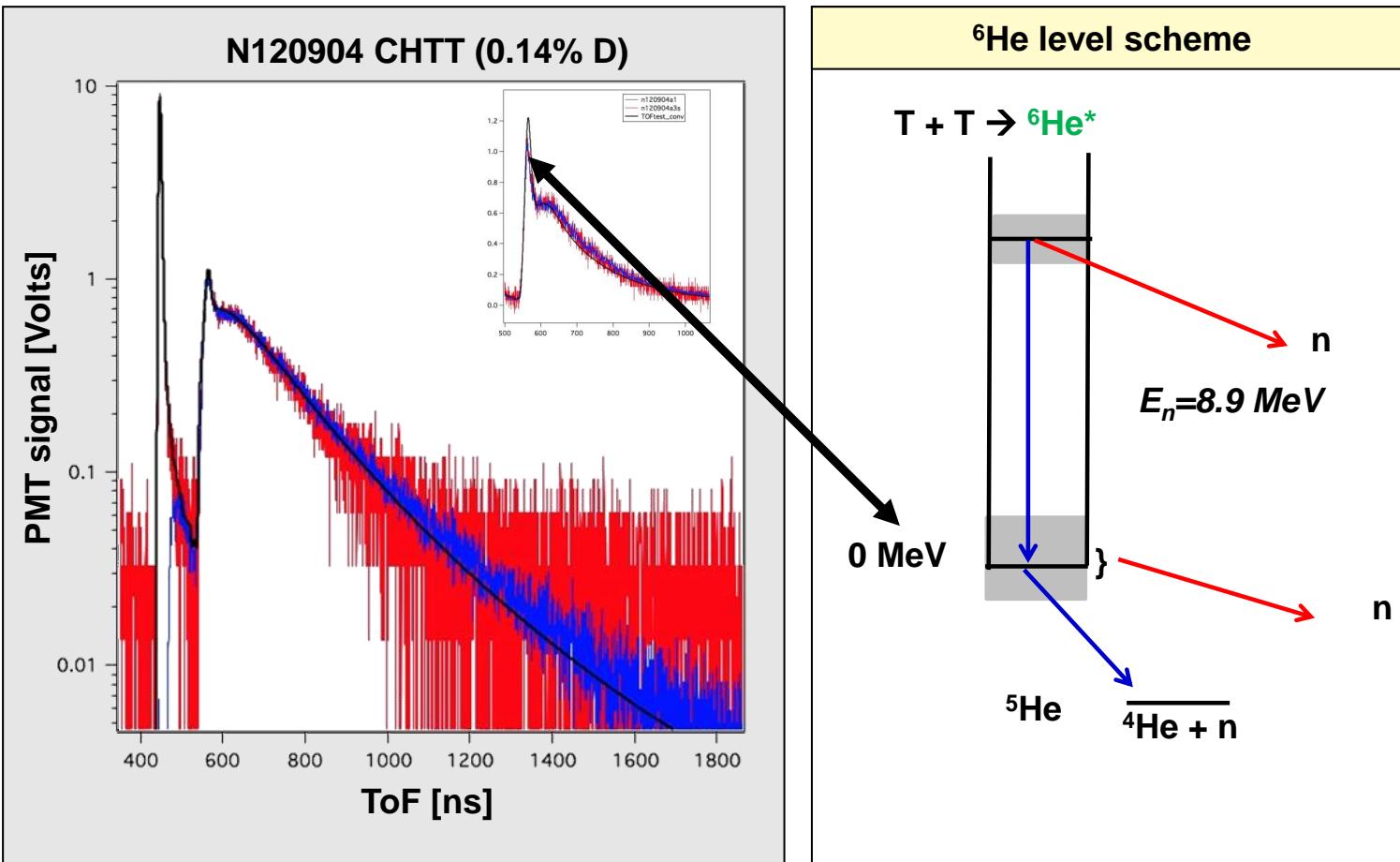


The NIF nuclear diagnostic team has obtained data from 58 “ride-along” experiments

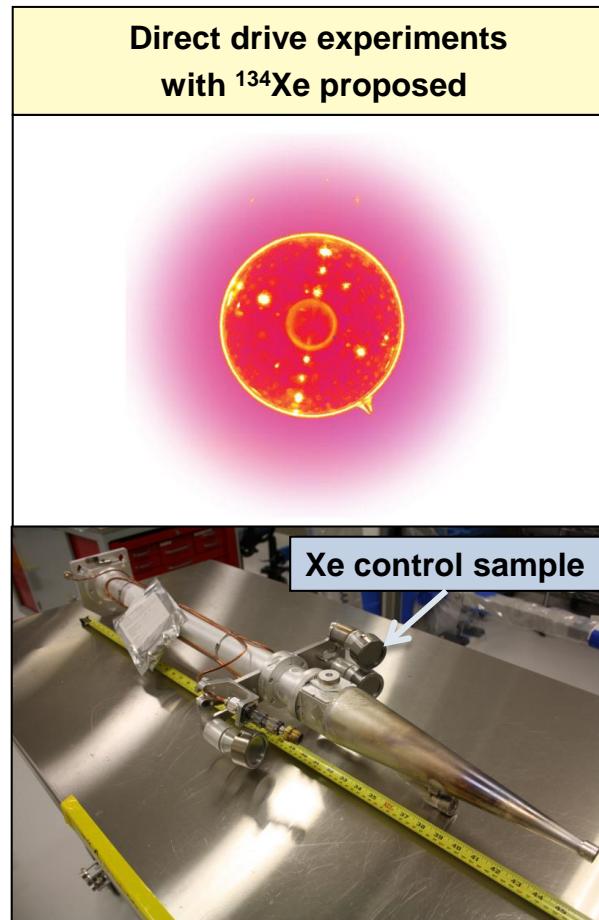
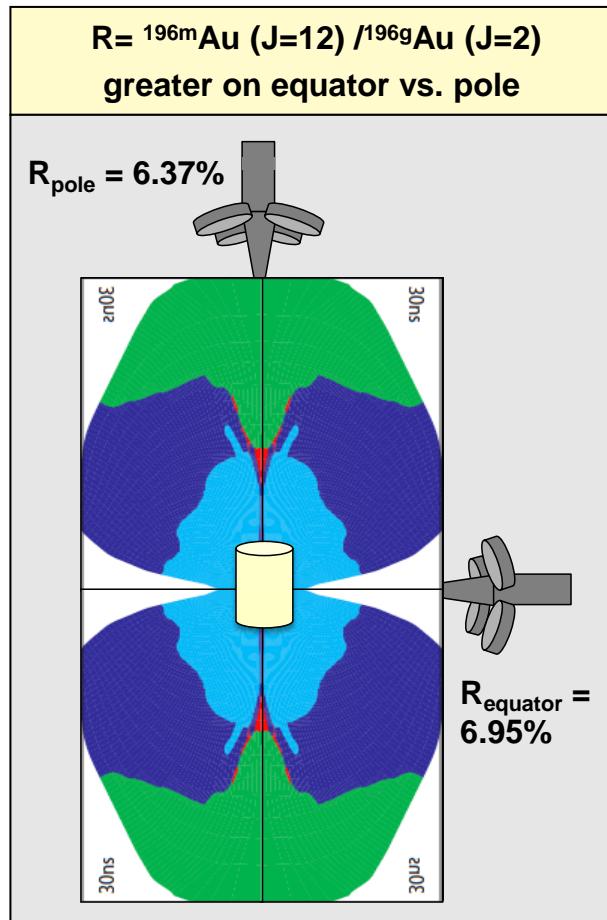
# Production of low energy neutrons in ICF implosions is important for nuclear cross sections for astrophysics and ICF $\rho R_{fuel}$ diagnostics



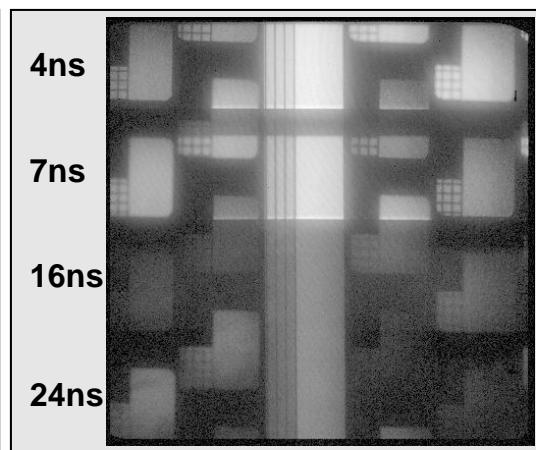
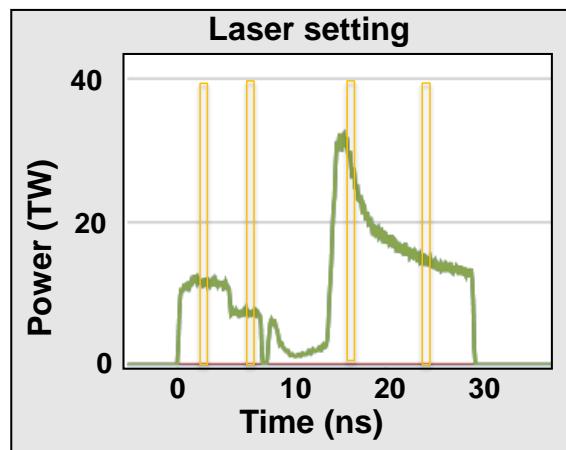
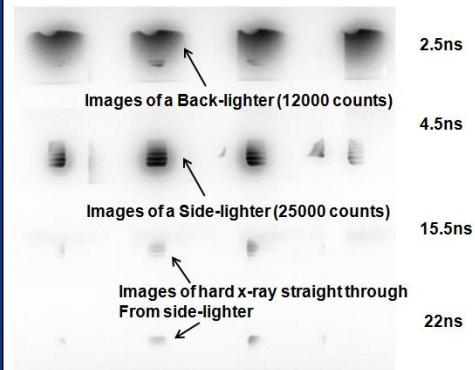
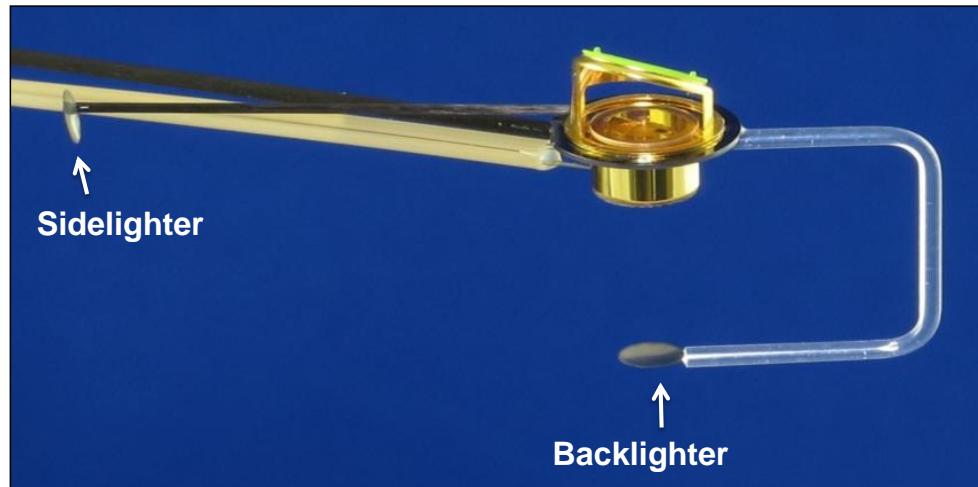
The NIF NTOF-20 system has for the first time  
observed the sequential decay of the T+T system in  
a HED plasma



## A tantalizing result: can we observe plasma effects on excited state populations?

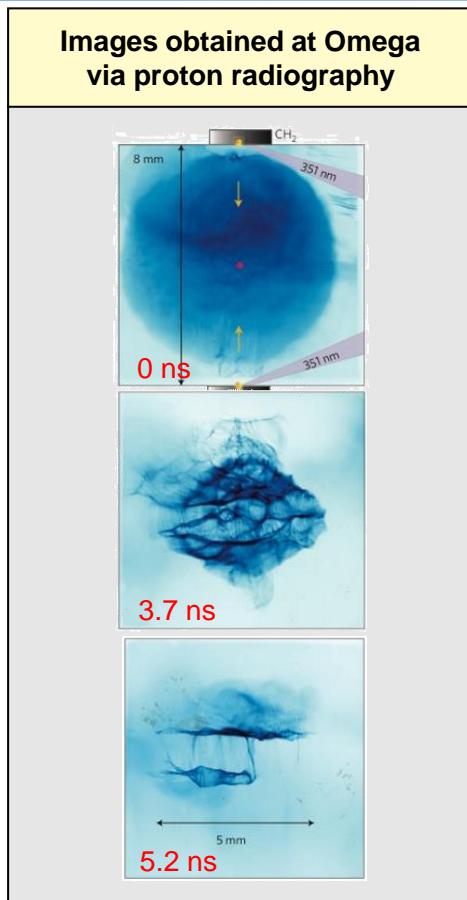


## The first LLNL-CEA ablative Rayleigh-Taylor experiment was conducted on March 21, 2013



- Hohlraum background and backlighter signal level verified to be adequate

# NIF collisionless shock experiment under development builds on results from Omega showing unexpected self-organizing stable field structures



**N. Kugland et al., Nature Physics (2012)**

**nature physics** LETTERS  
PUBLISHED ONLINE: 30 SEPTEMBER 2012 | DOI:10.1038/NPHYS2484

**Self-organized electromagnetic field structures in laser-produced counter-streaming plasmas**

N. L. Kugland<sup>1</sup>\*, D. D. Ryutov<sup>1</sup>, P-Y. Chang<sup>2</sup>, R. P. Drake<sup>3</sup>, G. Fiksel<sup>2</sup>, D. H. Froula<sup>2</sup>, S. H. Glenzer<sup>1</sup>, G. Gregori<sup>4</sup>, M. Grosskopf<sup>2</sup>, M. Koenig<sup>5</sup>, Y. Kuramitsu<sup>6</sup>, C. Kuranz<sup>3</sup>, M. C. Levy<sup>17</sup>, E. Liang<sup>7</sup>, J. Meinecke<sup>8</sup>, F. Minutti<sup>9</sup>, T. Morita<sup>6</sup>, A. Pelka<sup>9</sup>, C. Plechaty<sup>9</sup>, R. Presura<sup>9</sup>, A. Ravasio<sup>5</sup>, B. A. Remington<sup>1</sup>, B. Reville<sup>4</sup>, J. S. Ross<sup>1</sup>, Y. Sakawa<sup>6</sup>, A. Spitkovsky<sup>10</sup>, H. Takabe<sup>6</sup> and H-S. Park<sup>1</sup>

Self-organization<sup>12</sup> occurs in plasmas when energy progressively transfers from smaller to larger scales in an inverse cascade. Global structures that emerge from turbulent plasmas can be found in the laboratory<sup>4</sup> and in astrophysical settings; for example, the cosmic magnetic field<sup>13</sup>, collisionless shocks in supernova remnants<sup>1</sup> and the internal structures of newly formed stars known as Herbig-Haro objects<sup>14</sup>. Here we show that large, stable electromagnetic field structures can also arise within counter-streaming supersonic plasmas in the laboratory. The surprising structures, formed by a yet unexplained mechanism, predominantly oriented transverse to the primary flow direction, extend for much larger distances than the intrinsic plasma spatial scales and persist for much longer than the plasma kinetic timescales. Our results

CH<sub>2</sub> disc target (2 kJ, 3 ns)

Au disc (250 fs, 10 ps)

Protons

TCC

Film pack and proton images

CH<sub>2</sub>

**Design of NIF experiment**

Polar DIM CR39

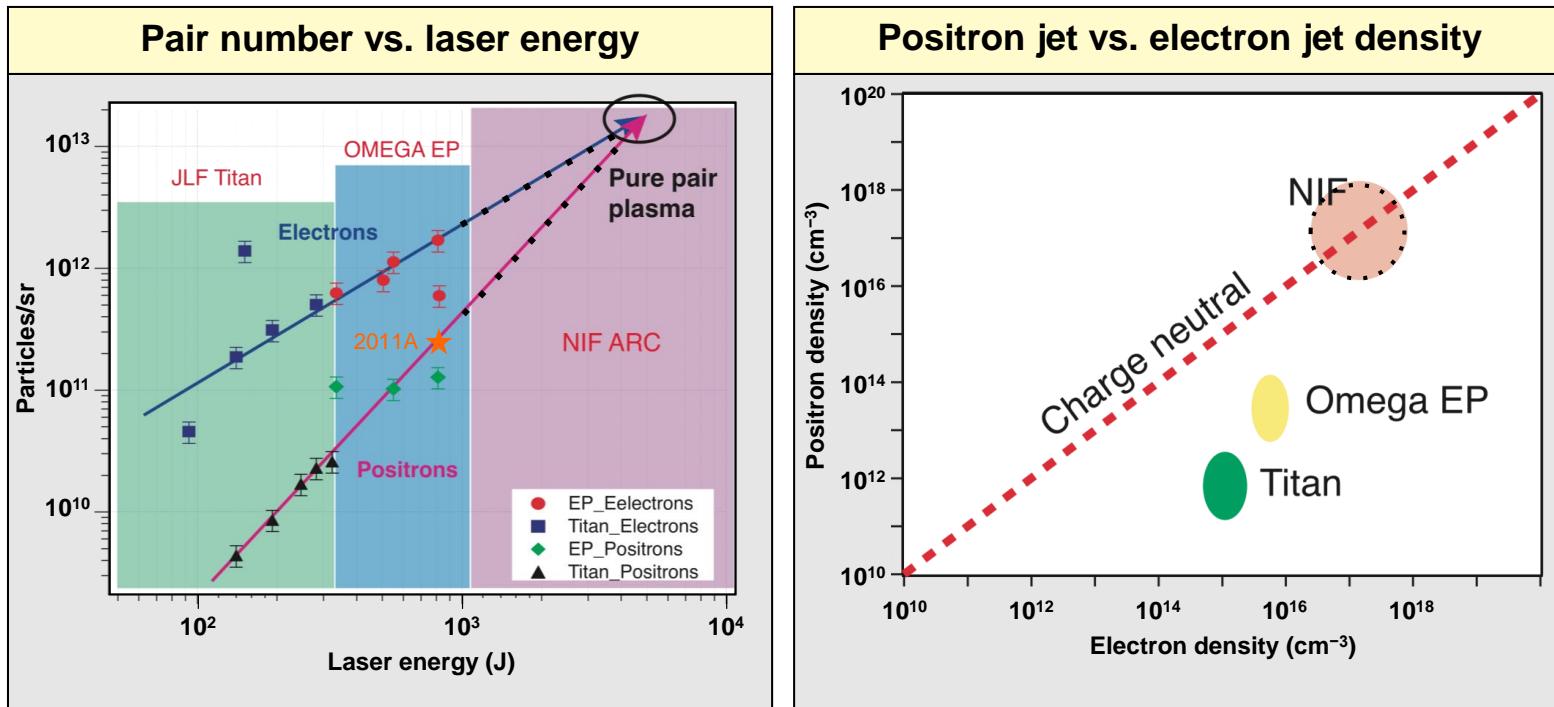
Ge doped CH foils

DHe3 Proton probe source

DIM90-78 MACS

100 kJ, 3-5 ns NIC CPP

## NIF will extend pair-plasma experiments to study of charge neutral systems (PI: H. Chen (LLNL))



**Bethe-Heitler process is dominant mechanism for production of e-/e+ pairs**



## NIF pair-plasma experiments will be the culmination of a multi-year, worldwide effort



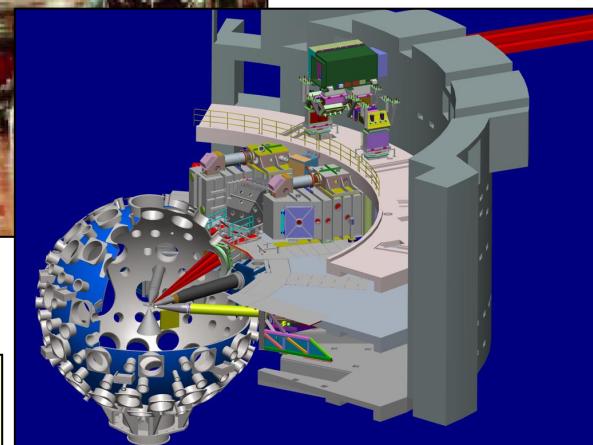
**Titan laser (LLNL)**  
1-10 ps, 100-350 J  
5-10 shots/day



**Omega EP (LLE)**  
1-10 ps, up to 1.3 kJ  
5 shots/day



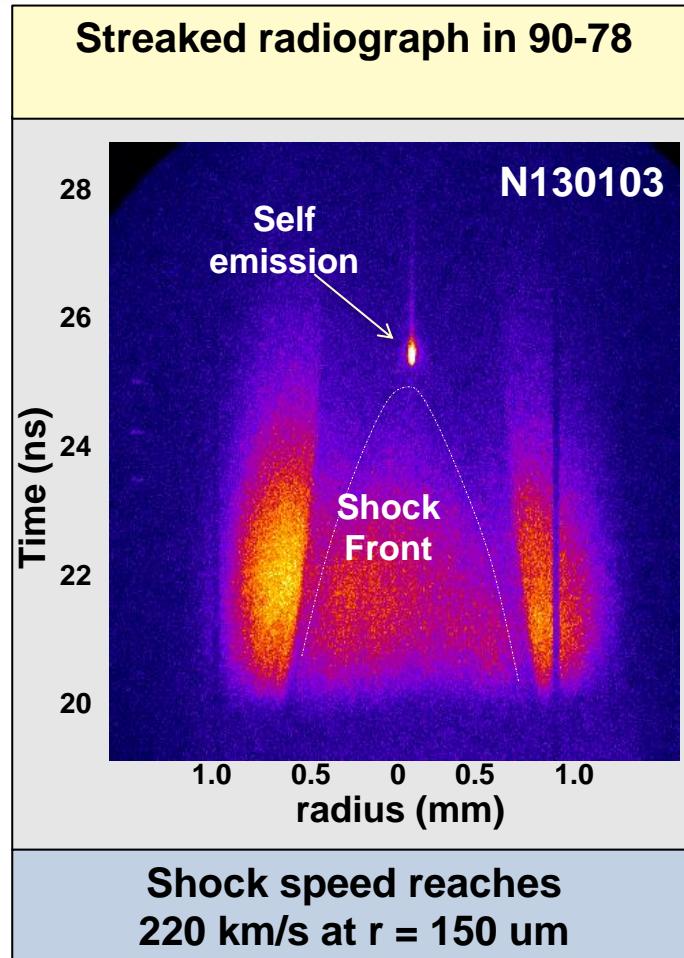
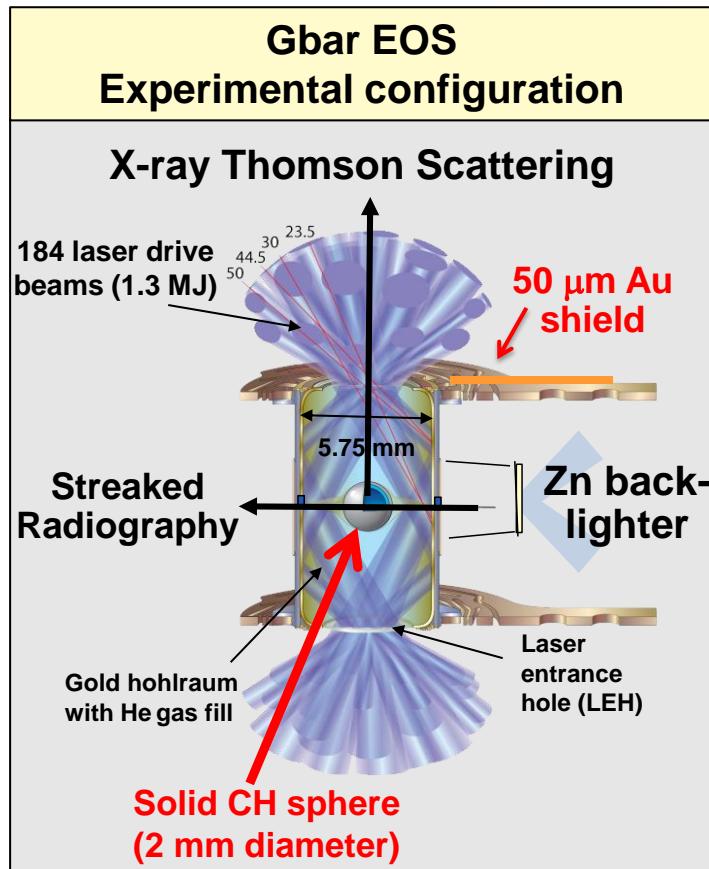
**Gekko (ILE)**  
4 beams, 1 ps, ~1 kJ  
Shots in 2012



**NIF ARC (LLNL)**  
1-50 ps, up to 10 kJ

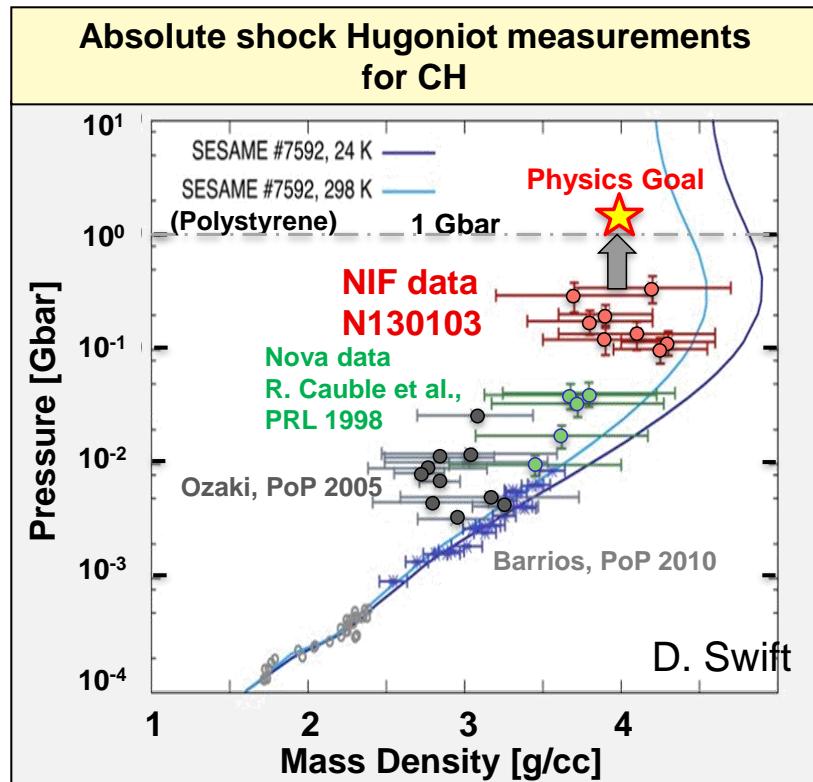
- 9 experiments conducted in the past year at Titan, Omega, Gekko, Orion (UK)
- 3 published papers, 2 submitted
- 2 theses in progress

We successfully fielded first NIF Gbar EOS fundamental science experiment in early January 2013 (N130103)





## First NIF Gbar EOS experiment demonstrated Hugoniot measurement at ~10x higher pressures compared to NOVA data

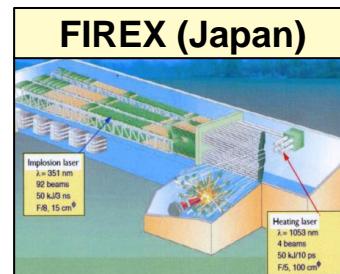
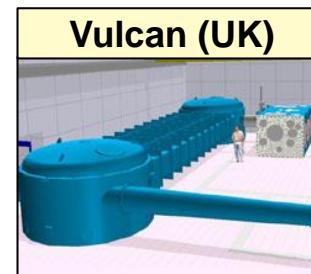
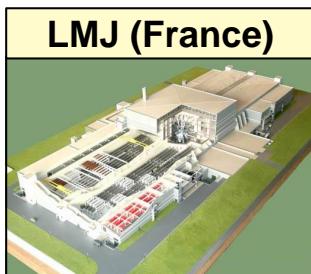
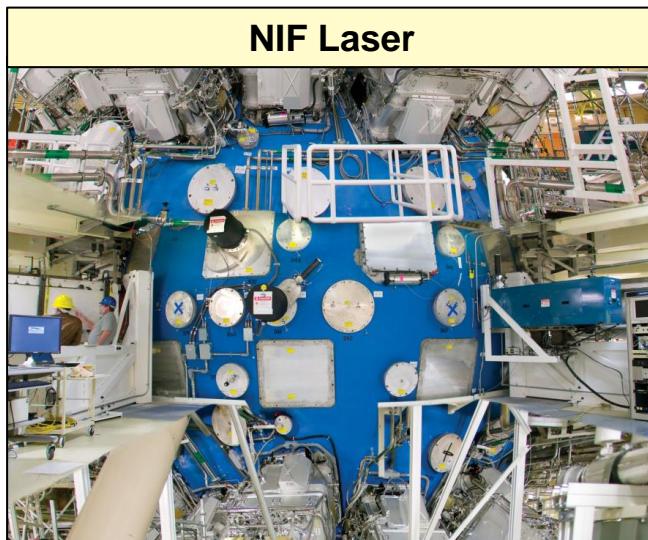
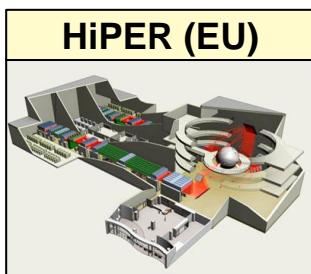


- More detailed data analysis in progress
- N130103 was cryogenic expt., previous data at ambient temperature
- Need to increase hohlraum drive to reach Gbar pressure in ingoing shockwave

Further experiments are planned this summer



**Summary: Science on HED facilities is growing rapidly worldwide- please join us!**





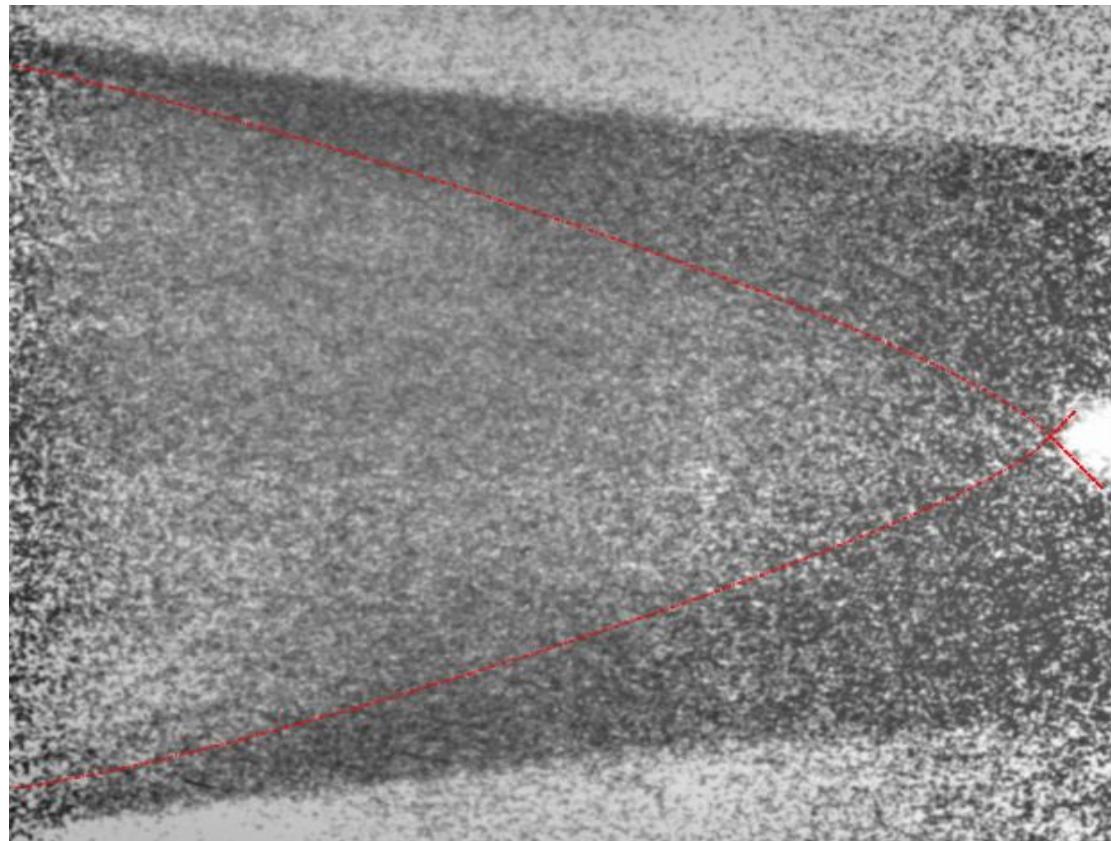
67

1557





**The shock front can be clearly identified for  
radii > 150 um**



**Shock speeds up  
to 220 km/s at  $r =$   
150 um, and up to  
260 km/s at shock  
convergence**

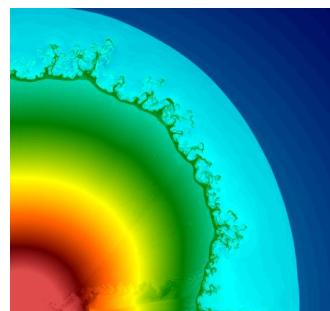
time

## Hydrodynamics

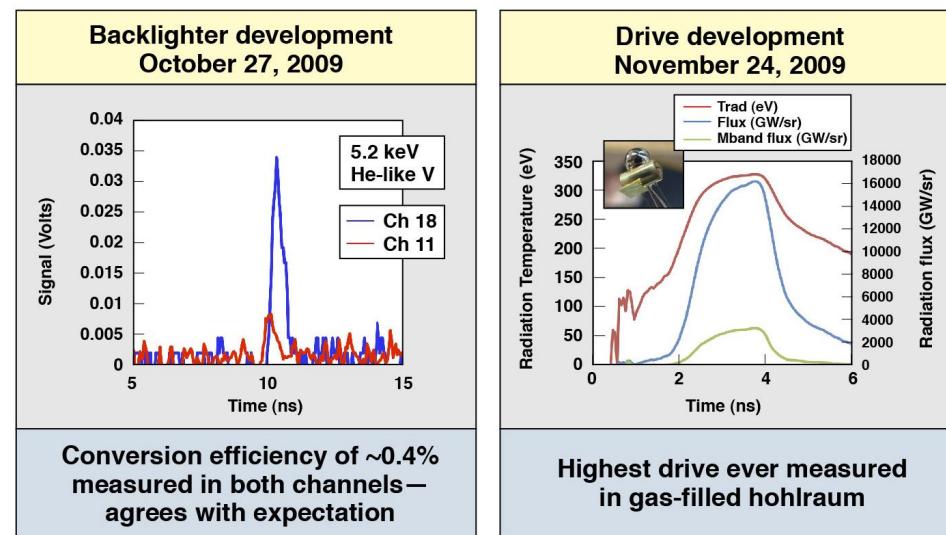
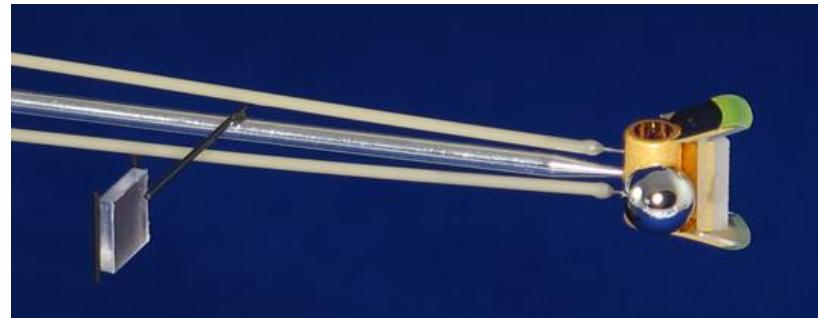
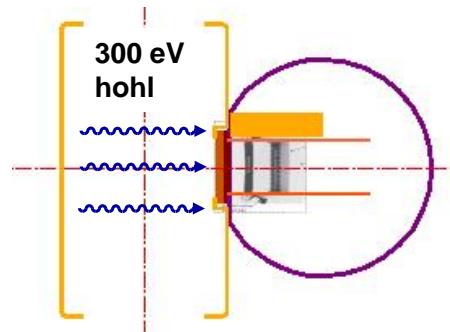


The first university experiments at NIF were conducted to study effect of radiative shock on supernova hydrodynamics

Radiative effects on the Rayleigh-Taylor instability is relevant to core-collapse, red supergiant  
(Kuranz, Park et al)



(SN simulation by Plewa)



Integrated experiment will be performed this FY

## Materials

# Jupiter/Omega results discovered a new solid-solid phase transition in MgO - effect on planetary structure



### REPORTS

(Fig. 3A). Pt deposition resulted in three distinct levels of contrast that reflect the surface height, with the lowest level being the original Au terrace (Fig. 3B). The same three-level structure was observed independently of deposition time up to 500 s (Fig. 3C). The middle contrast level corresponds to a high density of Pt islands that covered ~85% of the Au surface with a step height of ~0.24 nm, consistent with XPS results. Inspection with a higher rendering contrast revealed a ~10% coverage of a second layer of small Pt islands with a step height ranging between 0.23 and 0.26 nm (Fig. 3D). Step positions associated with the flattened island substructure were preserved, with negligible expansion or contraction of the 2D Pt islands occurring beyond the original terrace. The lateral size of the Pt islands was 2.02  $\pm$  0.38 nm, corresponding to an area of  $4.23 \pm 1.97 \text{ nm}^2$ . Incipient coalescence of the islands was constrained by surrounding (dark) narrow channels,  $2.1 \pm 0.25 \text{ nm}$  wide, that account for the remaining Pt-free portion of the first layer. The reentrant channels correspond to open Au terrace sites that were surrounded by adjacent Pt islands in what amounted to a huge increase in step density relative to the original substrate, the net geometric or electronic effect of which was to block further Pt deposition. The chemical nature of the inter-island region was assayed by exploiting the distinctive voltammetry of Pt and Au with respect to  $\text{H}_{\text{upd}}$  and oxide formation and reduction (Fig. 4B) and supplementary text.

Similar three-level Pt overlayers have been observed on monolayer films produced by molecular beam epitaxy (MBE) deposition at 0.05 monolayers per 200 Pa. Pt co-interaction with the decrease in surface energy that accompanies Au segregation was evident. In the present work, Pt monolayer formation was effectively complete within 1 s, giving a growth rate three orders of magnitude greater than in the MBE-STM study. Exchange of the deposited Pt with the underlying Au substrate was expected to be less developed. However, interesting and possible chemical contrast (i.e., the ligand effect) were evident on limited sections of the surface that were correlated with the original faulted geometry of the partially reconstructed Au surface. Upon lifting of the reconstruction, the excess Au atoms expelled mark the original fault location as linear 1D surface defects in the Pt overlayer (Fig. 3E). A simplified schematic of the self-terminating Pt deposition process in Fig. 3F describes how the  $\text{H}_{\text{upd}}$  accompanying incremental expansion of the 2D Pt islands can hinder the development of a second Pt layer, presumably by perturbation of the overlying water structure (17). This rapid process resulted in a much higher Pt coverage than that demonstrated by other methods, such as galvanic exchange reactions.

Because the saturated  $\text{H}_{\text{upd}}$  coverage is the agent of termination, reactivation for further Pt deposition was possible by removing the upper layer by sweeping or stepping the potential to positive values, e.g.,  $>0.2 V_{\text{SCSE}}$ , where negligible Pt de-

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**Acknowledgments.** We thank J. J. Malliet for his early work on the development of the electrochemical cell at negative potentials. This work was supported by NIST-Material Measurement Laboratory program. The x-ray photoelectron spectrometer was provided by National Recovery and Research Act (NRA) funds. Y. Li thanks the NIST-National Research Council Postdoctoral Fellow Program. The authors thank P. J. Cumpson for useful discussions. This work has received a provisional patent application (Atomic Layer Deposition of Pt from Aqueous Solutions) based on this work.

**Supplementary Materials**  
[www.sciencemag.org/content/338/6122/1227/DC1](http://www.sciencemag.org/content/338/6122/1227/DC1)  
 Materials and Methods  
 Supplementary Text  
 Figs. S1 and S2  
 References (26)  
 16 August 2012; accepted 17 October 2012  
 10.1126/science.1228925

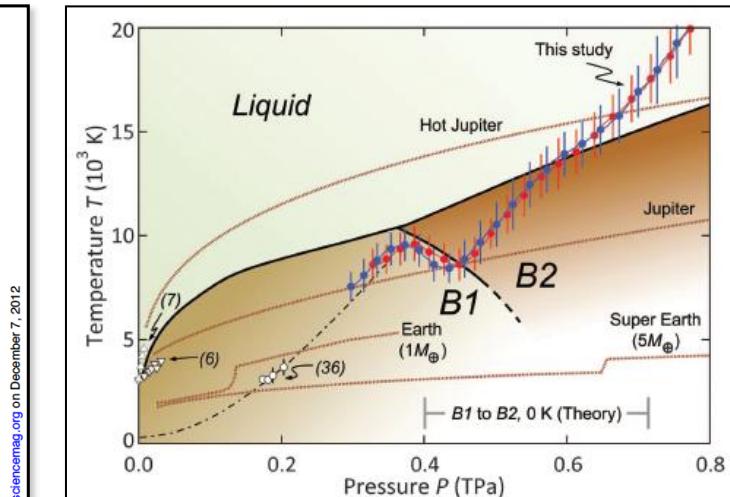
## Phase Transformations and Metallization of Magnesium Oxide at High Pressure and Temperature

R. Stewart McWilliams,<sup>1,2,†</sup> Dylan K. Spaulding,<sup>2,‡</sup> Jon H. Egger,<sup>4</sup> Peter M. Celliers,<sup>4</sup> Damien G. Hicks,<sup>3</sup> Raymond F. Smith,<sup>3</sup> Gilbert W. Collins,<sup>3</sup> Raymond Jeanloz,<sup>2,§</sup>

Magnesium oxide (MgO) is representative of the rocky materials comprising the mantles of terrestrial planets, such that its properties at high temperatures and pressures reflect the nature of planetary interiors. Shock-compression experiments on MgO to pressures of 1.4 terapascals (TPa) reveal a sequence of two phase transformations: from B1 (sodium chloride) to B2 (cesium chloride) crystal structures above 0.26 TPa, and from electrically insulating solid to metallic liquid above 0.60 TPa. The transitions exhibit large latent heats that are likely to affect the structure and evolution of Earth-like planets. Together with data on other oxide liquids, we conclude that magnesia deep inside terrestrial planets can be electrically conductive, enabling magnetic field–dynamo action within oxide-rich regions and blurring the distinction between planetary mantles and cores.

**M**agnesium oxide (MgO) is among the simplest oxides constituting the rocky mantles of terrestrial planets such as

Earth and the cores of Jupiter and other giant planets. Present in Earth's mantle as an end-member component of the mineral  $(\text{Mg},\text{Fe})\text{O}$  magnesiowüstite,



Downloaded from www.sciencemag.org on December 7, 2012

- Established solid-solid phase transition for the first time
- Metallization above 6 Mbar – dynamo effect possible in deep mantles
- Unexpectedly large latent heats

Stewart, et al.  
 Coppari, et al.



# JLF results on hot electron production

PRL 108, 115004 (2012) PHYSICAL REVIEW LETTERS week ending 16 MARCH 2012

**Hot Electron Temperature and Coupling Efficiency Scaling with Prepulse for Cone-Guided Fast Ignition**

T. Ma,<sup>1,2</sup> H. Sawada,<sup>2</sup> P. K. Patel,<sup>1</sup> C. D. Chen,<sup>1</sup> L. Divol,<sup>1</sup> D. P. Higgins,<sup>1,2</sup> A. J. Kemp,<sup>1</sup> M. H. Key,<sup>1</sup> D. J. Larson,<sup>1</sup> S. Le Pape,<sup>1</sup> A. Link,<sup>1,3</sup> A. G. MacPhee,<sup>1</sup> H. S. McLean,<sup>1</sup> Y. Ping,<sup>1</sup> R. B. Stephens,<sup>4</sup> S. C. Wilks,<sup>3</sup> and F. N. Beg<sup>2</sup>

<sup>1</sup>Lawrence Livermore National Laboratory, Livermore, California 94550, USA  
<sup>2</sup>University of California-San Diego, La Jolla, California 92093, USA  
<sup>3</sup>The Ohio State University, Columbus, Ohio 43210, USA  
<sup>4</sup>General Atomics, San Diego, California 92186, USA

(Received 3 December 2011; published 16 March 2012)

The effect of increasing prepulse energy levels on the energy spectrum and coupling into forward-going electrons is evaluated in a cone-guided fast-ignition relevant geometry using cone-in-wire targets irradiated with a high intensity ( $10^{19} \text{ W/cm}^2$ ) laser pulse. Hot electron temperature and flux are inferred from  $K\alpha$  images and yields using hybrid particle-in-cell simulations. A two-temperature distribution of hot electrons was required to fit the full profile, with the ratio of energy in a higher energy (MeV) component increasing with a larger prepulse. As prepulse energies were increased from 8 mJ to 1 J, overall coupling from laser to all hot electrons entering the wire was found to fall from 8.4% to 2.5% while coupling into only the 1–3 MeV electrons dropped from 0.57% to 0.03%.

DOI: 10.1103/PhysRevLett.108.115004 PACS numbers: 52.50.Jm, 52.38.Kd, 52.38.Mf, 52.70.La

Fast Ignition (FI) [1,2] is an approach to inertial confinement fusion (ICF), in which a precompressed deuterium-tritium fuel is rapidly driven to ignition by an external heat source. This scheme can ignite lower density fuel leading, in principle, to higher gains than possible with conventional ignition if the reentrant cone approach to FI, a hollow cone is embedded in the fuel capsule to provide an open-vacuum path free of coronal plasma for an intense laser beam to generate a flux of energetic electrons at the tip of the cone which can then propagate to the compressed fuel core. However, the presence of preformed plasma in the cone arising from the intense laser prepulse which ablates the inner cone wall, can strongly affect the spatial, energy-spectral, and angular characteristics of these laser-generated hot electrons and thus the efficiency with which their energy can be coupled to the core.

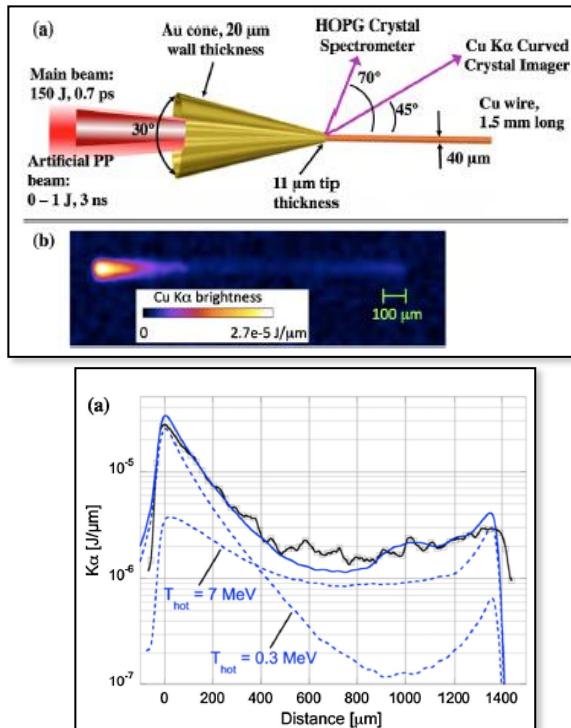
Previous works by Batou *et al.* [3] and Van Woerkom *et al.* [4] showed that significant prepulse could have a detrimental effect on coupling to the cone tip. MacPhee *et al.* [5] demonstrated that even a small prepulse could result in significant filamentation of the laser beam in the preplasma, limiting the penetration of the laser, and accelerating energetic electrons transversely. These results were achieved using either imaging of  $K\alpha$  x-ray emission from the cone target itself or measuring the intensity of the  $K\alpha$  spot in a region beyond the cone tip. However, while these techniques provided a spatial distribution of  $K\alpha$  in various areas of the interaction, no spectral information regarding the electron flux could be inferred. Comparisons of preplasma versus no preplasma conditions by Batou *et al.* were achieved by doubling the fundamental laser frequency to create a high contrast. This provided a clean interaction surface for the main laser, but complicated the

comparison, as the absorption mechanisms would be different for the very different  $IA^2$ . In the MacPhee *et al.* study, electrons were electrostatically confined within the isolated cone target. The significant amount of recirculation of the hot electrons within the cone walls and plasma allows only limited conclusion of the electron source at the cone tip by either the experiments or simulations.

In this Letter, we present the first quantitative scaling of coupling as a function of prepulse in an intense laser-cone interaction. Through the use of cone-wire targets [6], we demonstrate the existence of a two-temperature hot electron distribution within the target and characterize its flux and energy spectrum entering a 40  $\mu\text{m}$  diameter wire at the cone tip, and correlate these quantities with the amount of preformed plasma in the cone.

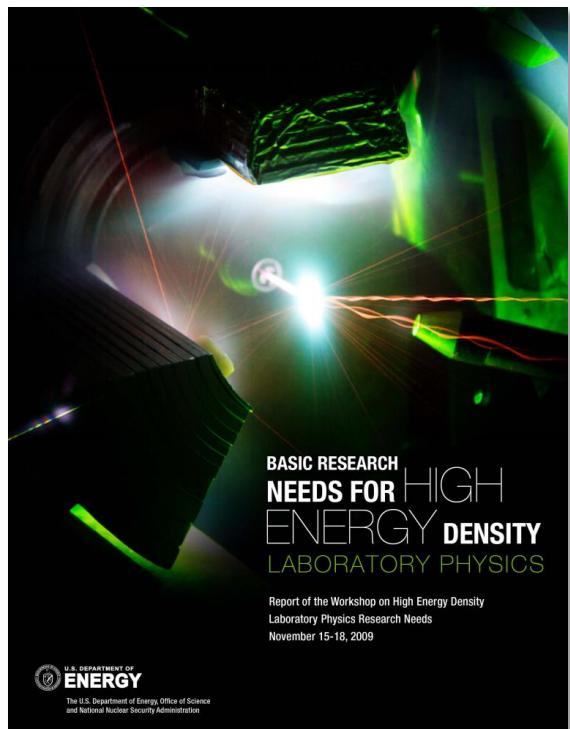
The experiment was performed on the Titan laser at LLNL, of  $\lambda_0 = 1.054 \mu\text{m}$  wavelength,  $150 \pm 10 \text{ J}$ , focused to an 8  $\mu\text{m}$  full width at half maximum (FWHM) focal spot in a  $0.7 \pm 0.2 \text{ ps}$  pulse length. The intrinsic prepulse of the laser was measured at  $8 \pm 3 \text{ mJ}$  in a 1.7 ms duration pulse prior to the main beam. Varying prepulse levels, up to 1 J, were produced by injecting an auxiliary nanosecond-duration laser colinear with the main short pulse laser. This auxiliary laser had a similar focal spot distribution as the main beam and was timed to overlap the intrinsic prepulse.

The target, shown in Fig. 1, was a 1 mm long Au hollow cone with 30° full opening angle, 20  $\mu\text{m}$  wall thickness, 30  $\mu\text{m}$  internal tip diameter, and 11  $\mu\text{m}$  tip thickness. A 1.5 mm long, 40  $\mu\text{m}$  diameter Cu wire was glued to the outer cone tip. The wire diameter is chosen to match the nominal 40  $\mu\text{m}$  optimum ignition hot spot diameter in a FI target [7], and its quasi 1D geometry allows for single shot



- K $\alpha$  emission follows hot electrons in wire
- Find 2-temperature distribution required
- Laser-to-hot-electron efficiency measured

The categorization in the 2009 Office of Science “Basic Research Needs” report provides an effective means to categorize HEDS research



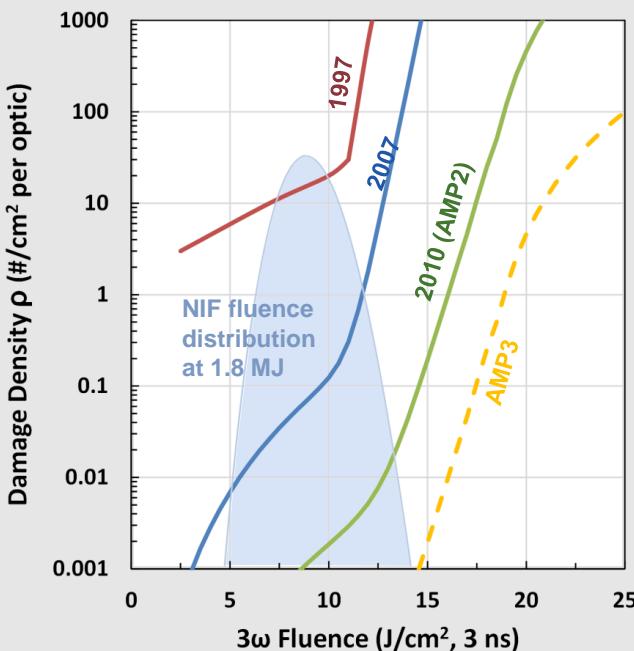
**Major areas of technical interest:**

- **High Energy Density Hydrodynamics**
- **Magnetized High Energy Density Plasma**
- **Nonlinear Optics of Plasmas**
- **Radiation-Dominated Dynamics and Material Properties**
- **Relativistic HED Plasmas and Intense Beam Physics**
- **Warm Dense Matter**
- **High-Z Multiply Ionized HED Atomic Physics**
- **Diagnostics**

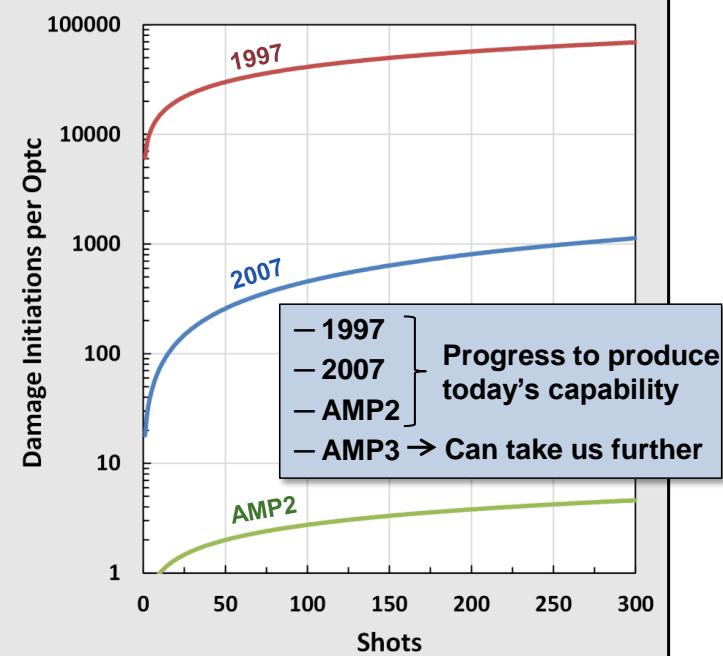


## Dramatic improvements in optical damage thresholds have been developed to enable high-energy operations

### Improvement in fused silica surface finish from 1997 to present

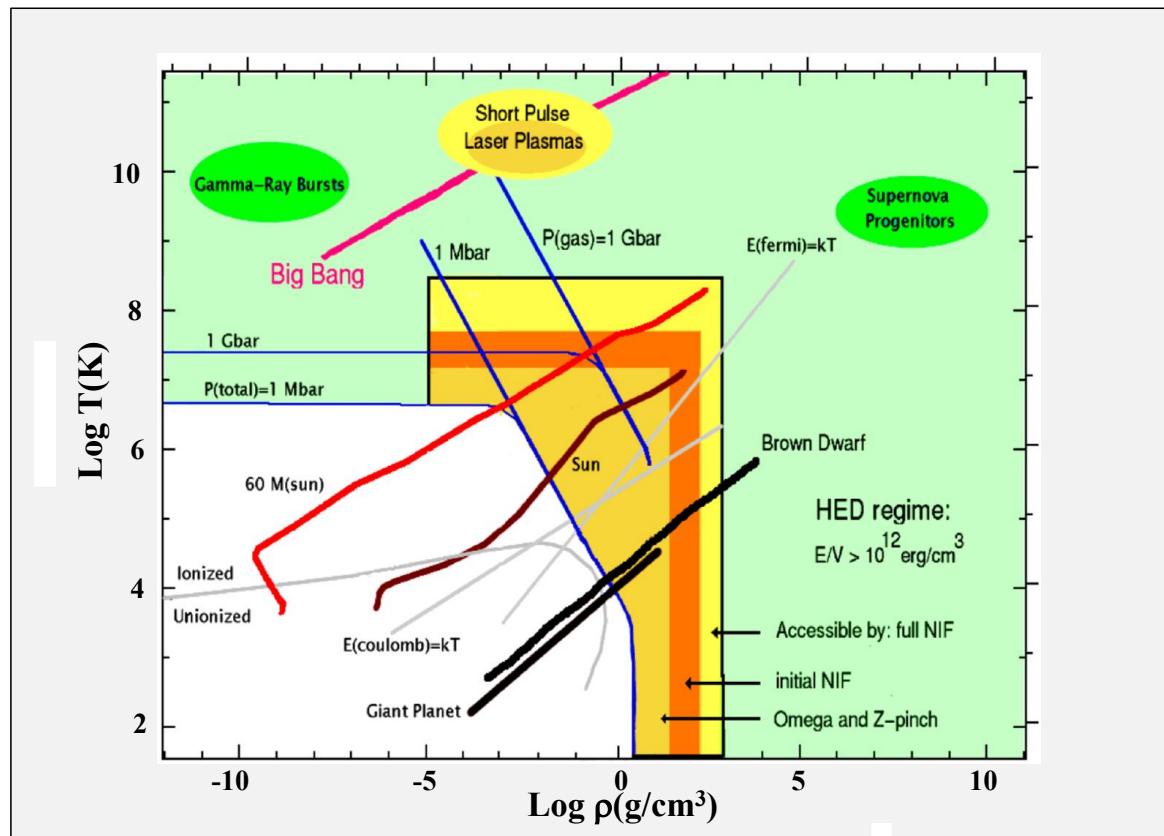


### Improvement in damage initiation at 1.8 MJ, 3 ns





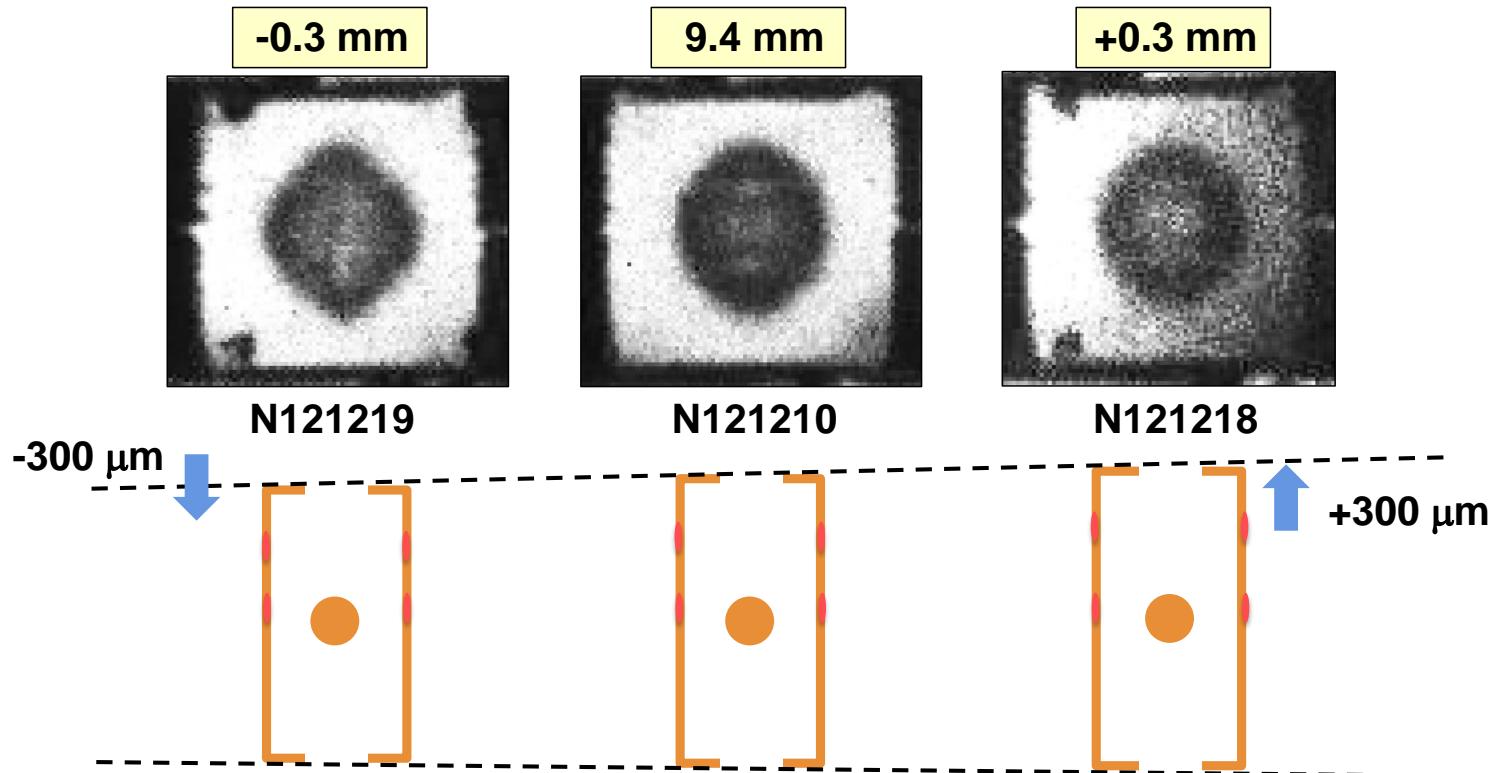
## 2003 NRC Report on High Energy Density Physics defines HED science as $P > 1$ Mbar ( $10^{11}$ J/m<sup>3</sup>)





Recent data show that P4 asymmetry can be modified by extending the hohlraum length

Nominal length hohlraum



X-ray drive symmetry must be controlled to the ~1% level



**NIF has conducted nearly 1300 shots since start of operations in spring 2009**

Type	Purpose	Total
Target shots-	Stockpile Stewardship- Inertial confinement fusion	259
Program data	Stockpile Stewardship- HED science	145
	DOD and other national security	17
	Fundamental science	15
Target shots- Capabilities	Target diagnostics commissioning/calibration; Capability development; System qualification	191
Laser shots	Laser/optics performance and calibration	661
<b>Total (through 6/4/13)</b>		<b>1288</b>

## NIF fundamental science experiments

Topic	PI Last	PI Institution
Carbon and Iron Equation of State	T. Duffy/ R. Jeanloz	Princeton/UCB
Supernova hydrodynamics- Radiative Effects (Rad SNRT)	C. Kuranz	Univ. of Michigan
Novel phases of compressed diamond	J. Wark/ J. Eggert	Oxford/LLNL
Nucleosynthesis and the s-process	L. Bernstein	LLNL
Rayleigh-Taylor instability and astrophysical implications (merged proposal)	A. Casner/ V. Smalyuk J. Kane	CEA LLNL
Matter at ultra-high densities (merged proposal)	P. Neumayer R. Falcone	GSI UC Berkeley
Hydrogen and methane at ultra-high pressures (merged proposal)	R. Jeanloz R. Hemley	UC Berkeley Carnegie Institution of Washington
Diverging Supernova hydrodynamics	T. Plewa	FSU
Astrophysical collisionless shocks (merged proposal)	Y. Sakawa G. Gregori	Osaka University Univ. of Oxford
Relativistic pair plasmas	H. Chen	LLNL